Hunting New Physics in the Dark Universe

FLATIRON INSTITUTE

Elena Pinetti

TEVPA2026

ROADMAP

Dark Matter Messengers → Gamma-Ray to Radio Searches → Future Directions

Mass of dark matter unknown!

10^{-19}eV	μeV	eV	keV	MeV	GeV	10^2 TeV	10^5 TeV	(…)

Fuzzy | Dark Photon, Axion, … | Sterile $\boldsymbol{\nu}$, … | WIMPs, … | Ultra-Heavy | PBH

Multi-Messenger Searches of Dark Matter

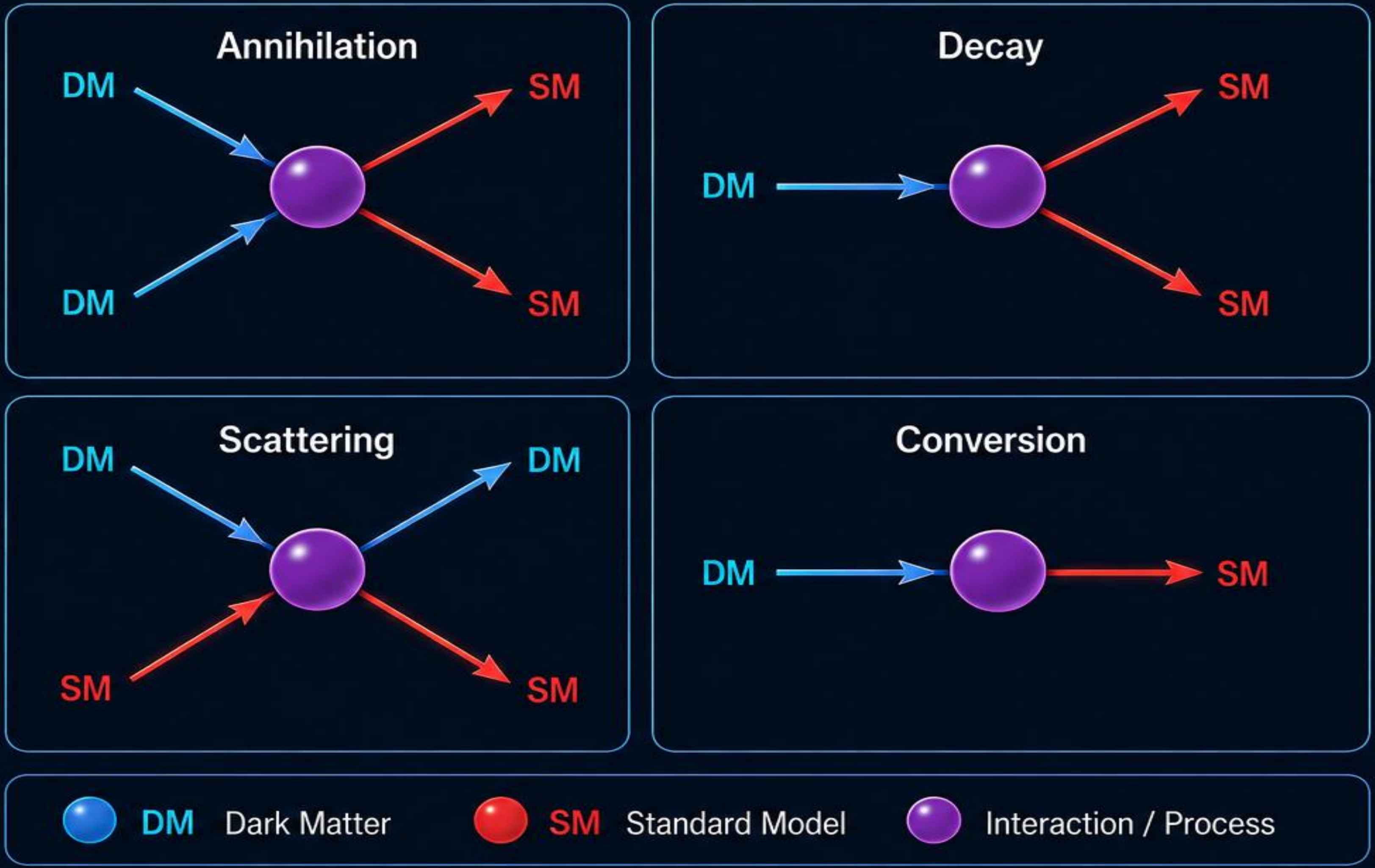
Detection of signals from DM annihilation, decay or interactions in the cosmos

Common assumptions:

- ☑ New Physics
- ☑ Stable (long-lived)
- ☑ Interactions with Standard Model

Cosmic messengers:

- ☑ Photons
- ☑ Neutrinos
- ☑ Charged cosmic rays



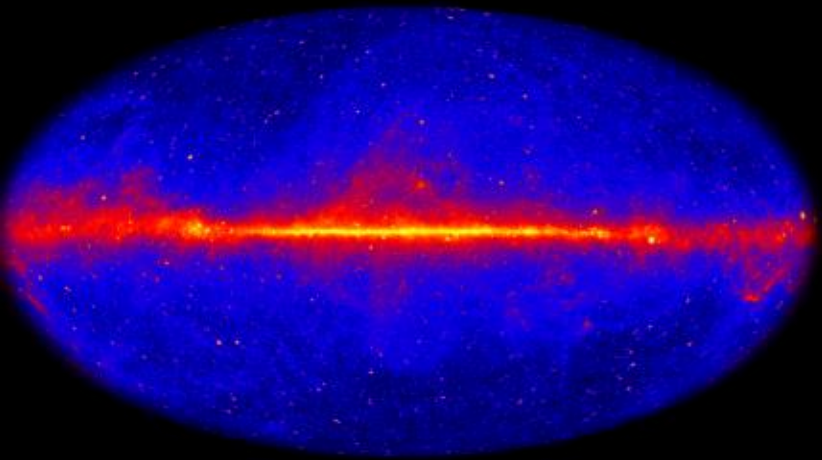
See Gonzalo Herrera's talk on New Physics with Cosmic Rays and Neutrinos


SIGNALS
VS
BACKGROUND

How do we discover dark matter?

1. Unique Signatures of Dark Matter
2. Modelling the Astrophysical Background
3. Promising Targets & Astrophysical Environments

Targets for Dark Matter

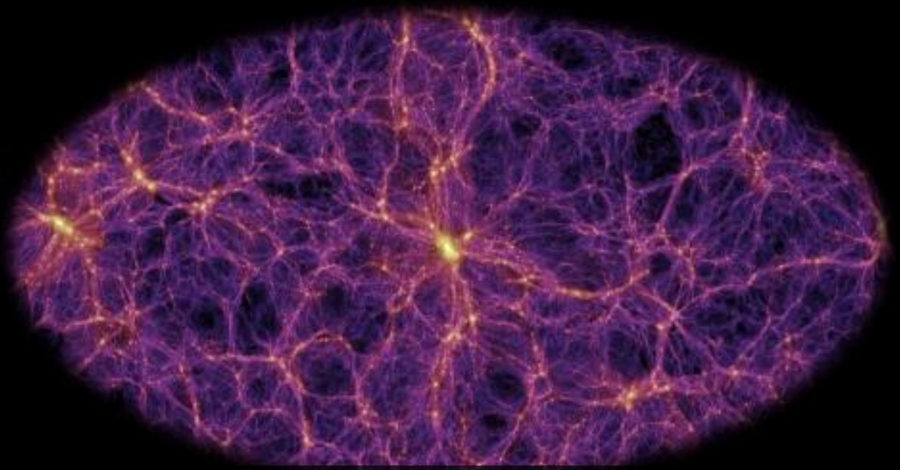


Galactic Center

Dwarf Galaxies

Clusters of Galaxies

Blank Sky



Cosmic Filaments

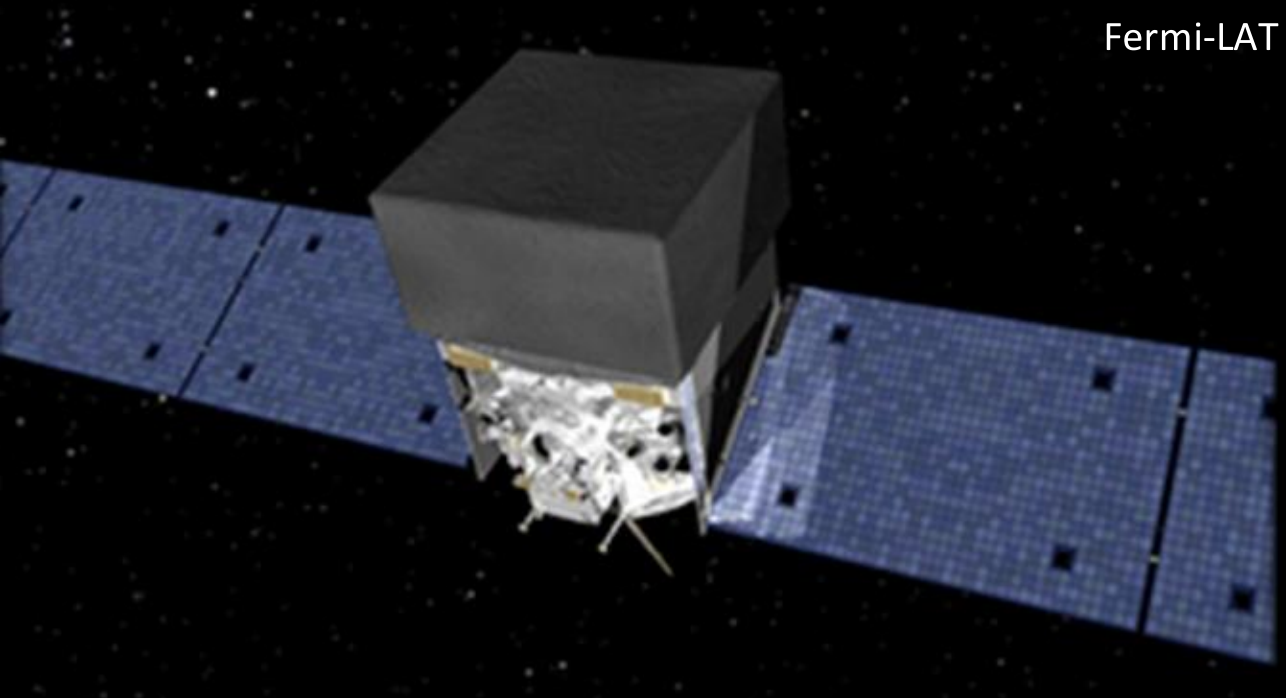
Cosmic Voids

ROADMAP

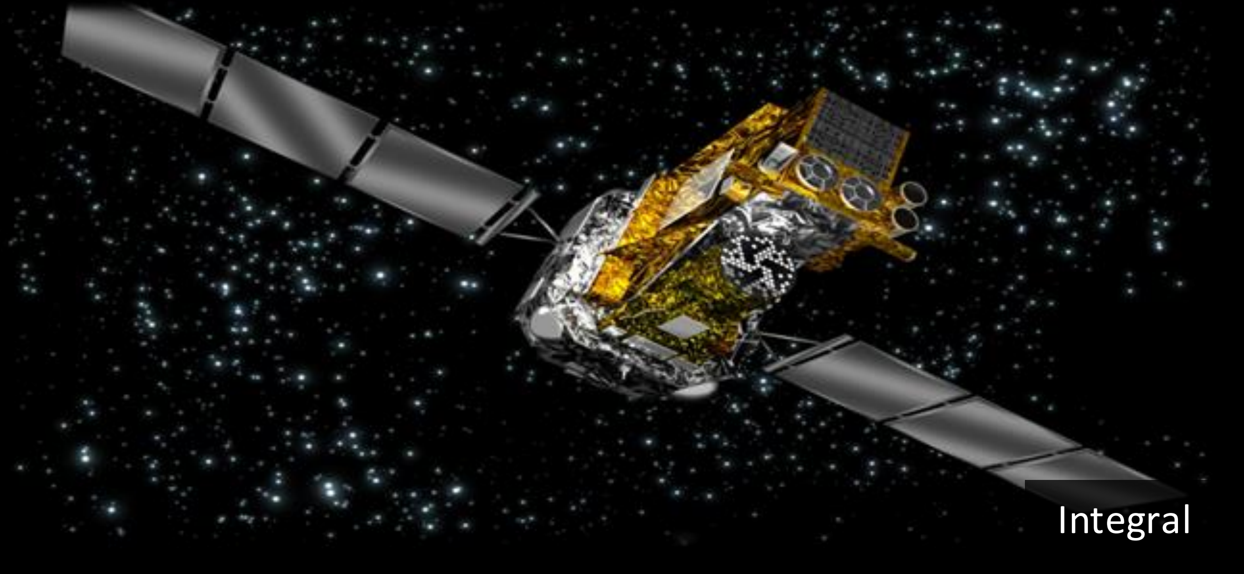
Dark Matter Messengers

Gamma-Ray to Radio Searches

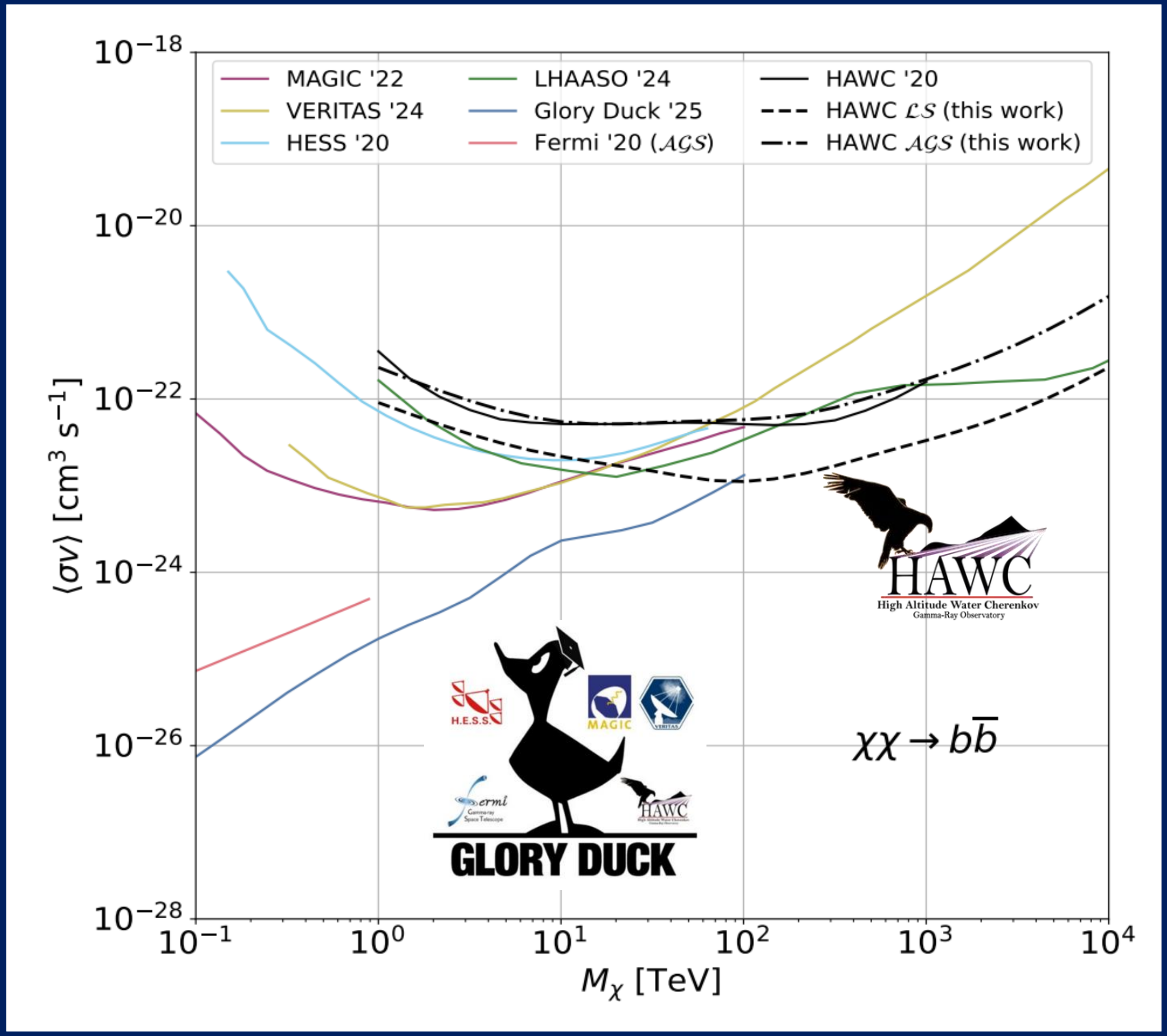
Future Directions



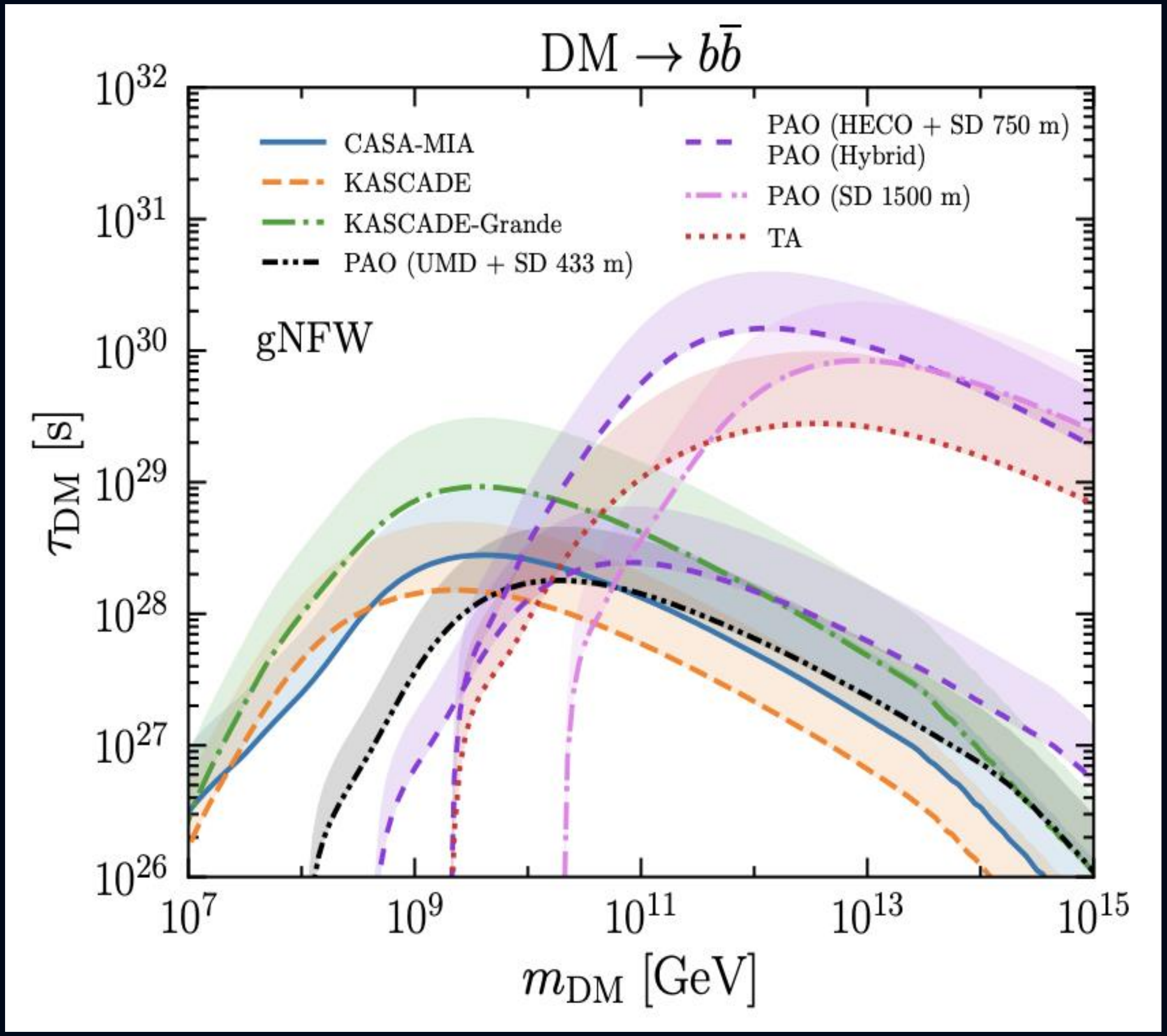
Dark matter searches with γ-rays and X-rays



Heavy Dark Matter Searches

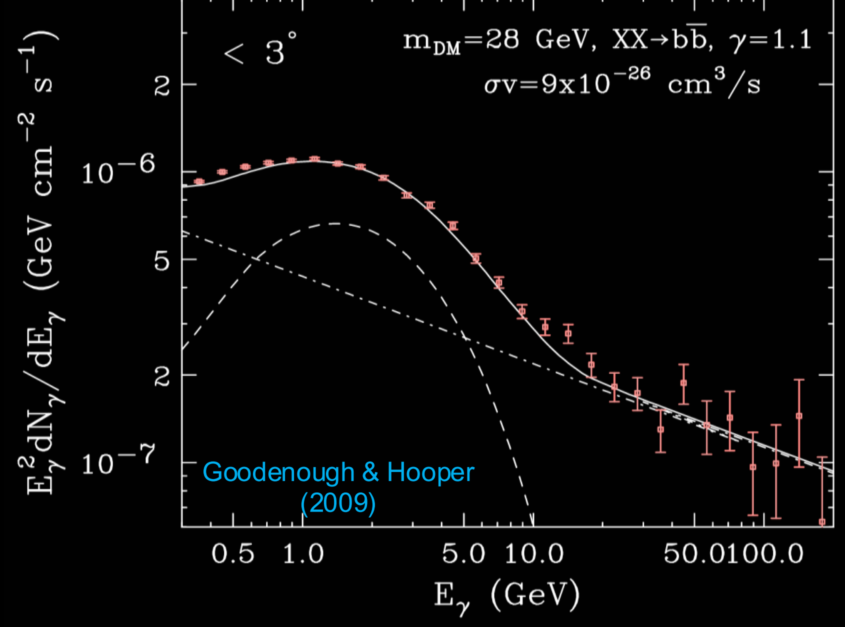


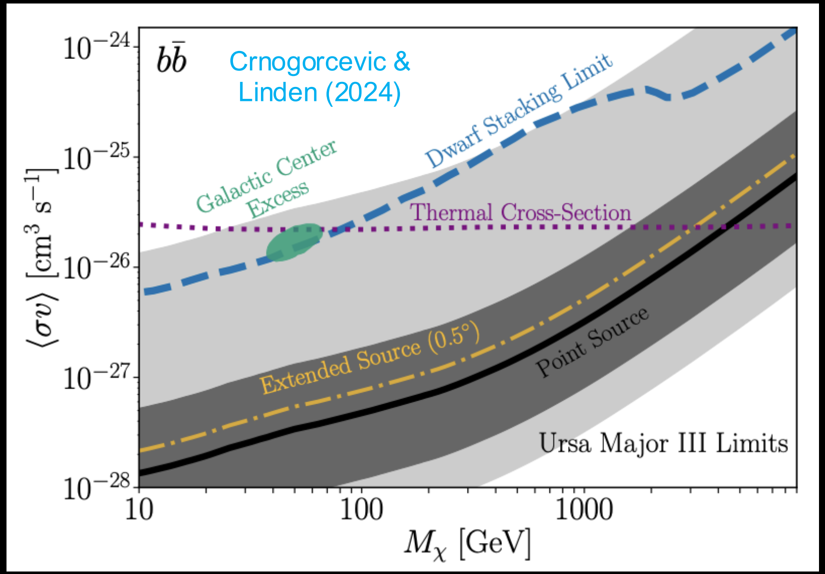
Adapted from HAWC Collaboration (2026)



Chianese et al (2026)

GeV Searches for Dark Matter

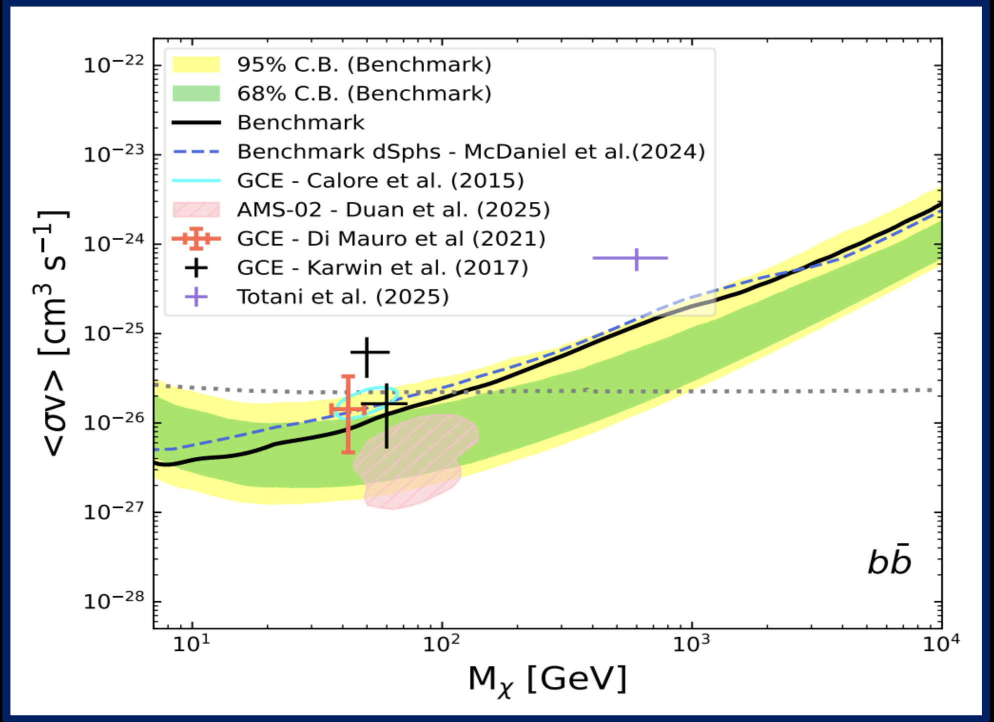




No Observational Evidence for Dark Matter Nor a Large Metallicity Spread in the Extreme Milky Way Satellite Ursa Major III / UNIONS 1

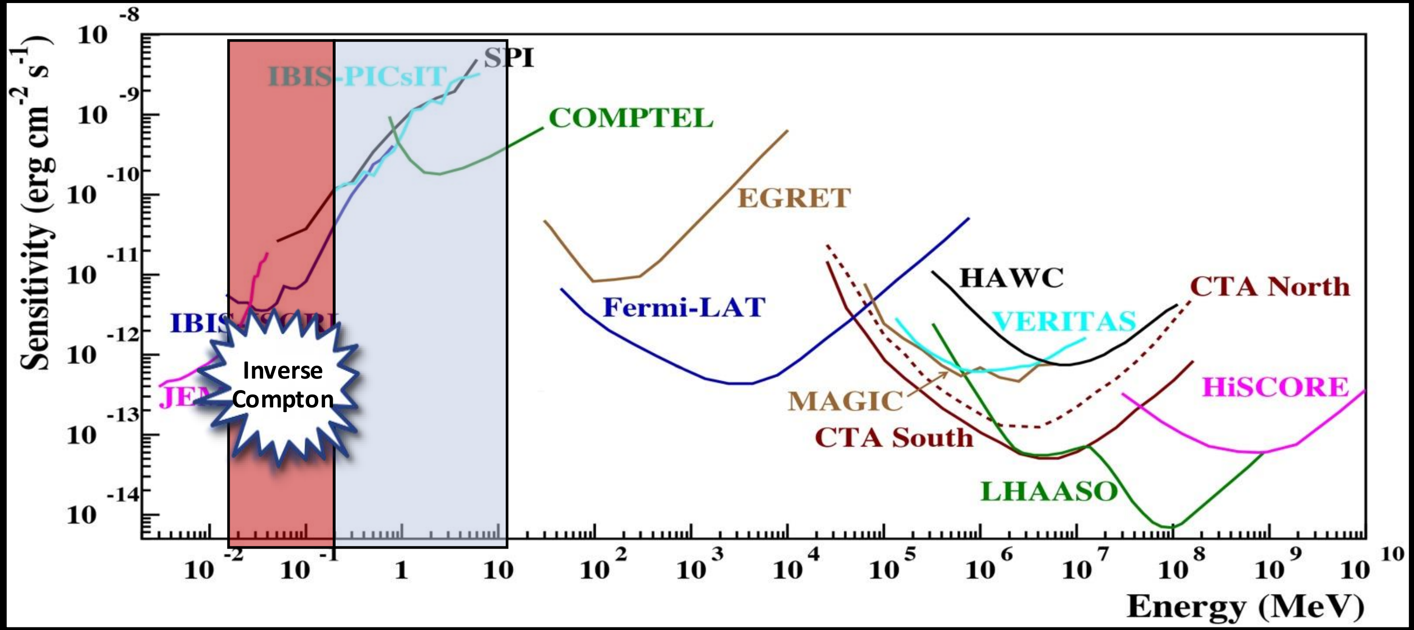
William Cerny,[1] Daisy Bissonette,[2] Alexander P. Ji,[2,3,4] Marla Geha,[1] Anirudh Chiti,[2,3] Simon E.T. Smith,[5] Joshua D. Simon,[6] Andrew B. Pace,[7] Evan N. Kirby,[8] Kim A. Venn,[5] Ting S. Li,[9] and Alice M. Luna[2,3]

Cerny et al, arXiv:2510.02431

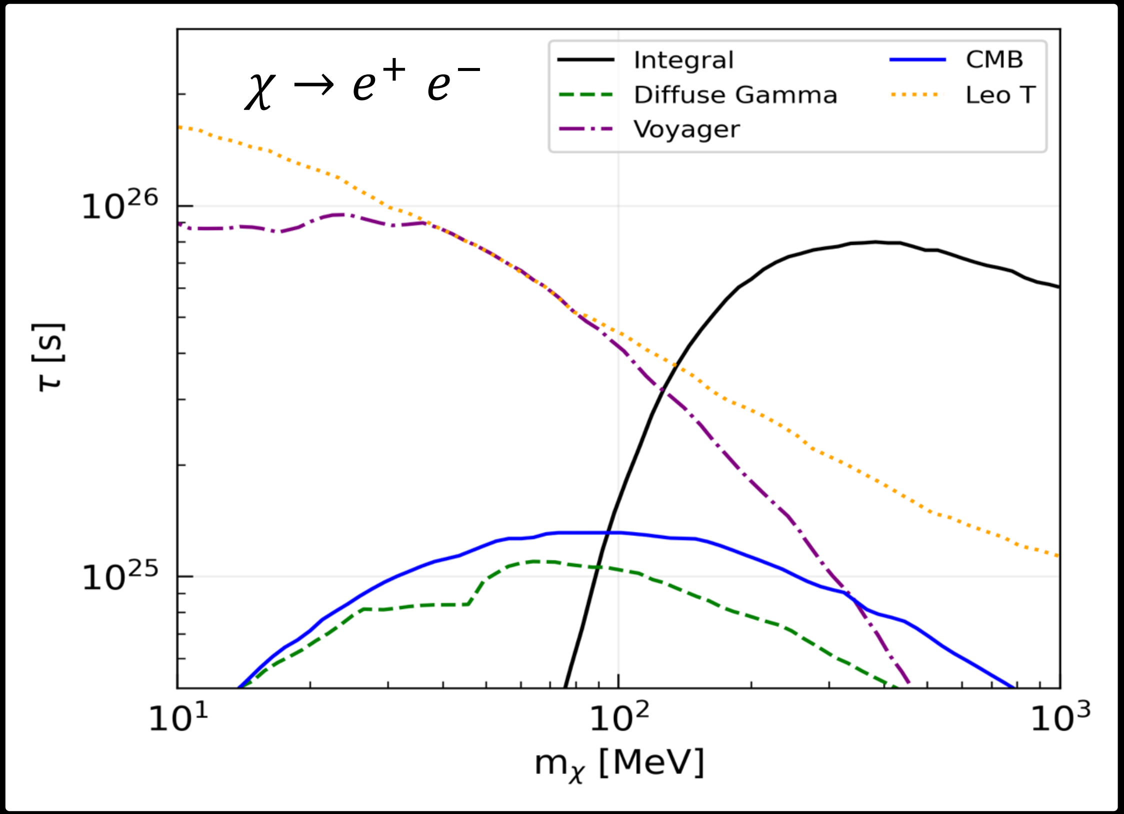


Circiello et al (2026)

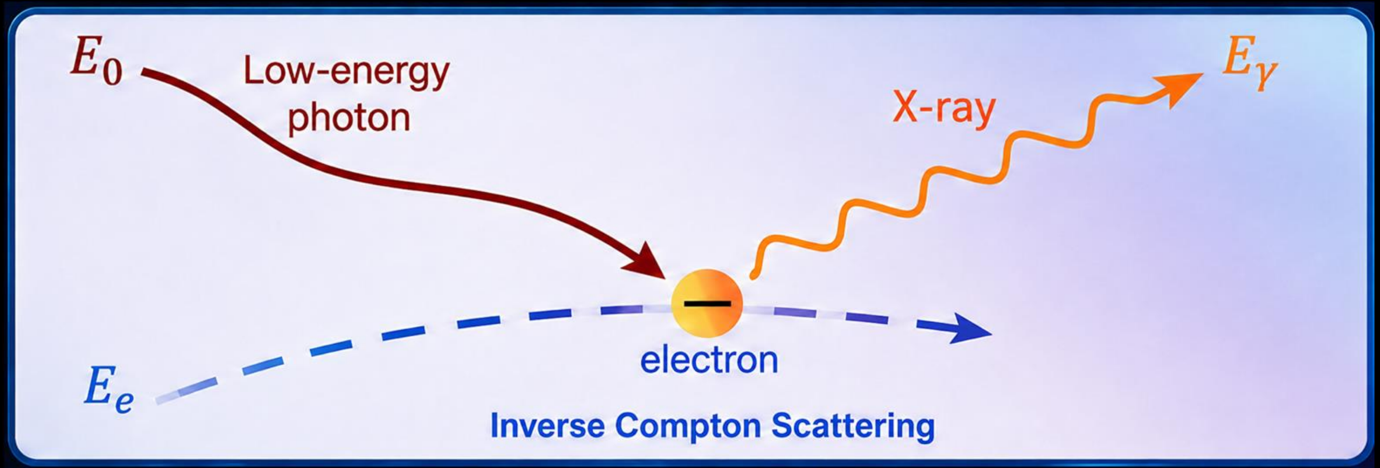
MeV Dark Matter



See John Tomsick's talk on MeV gamma-ray astronomy and COSI

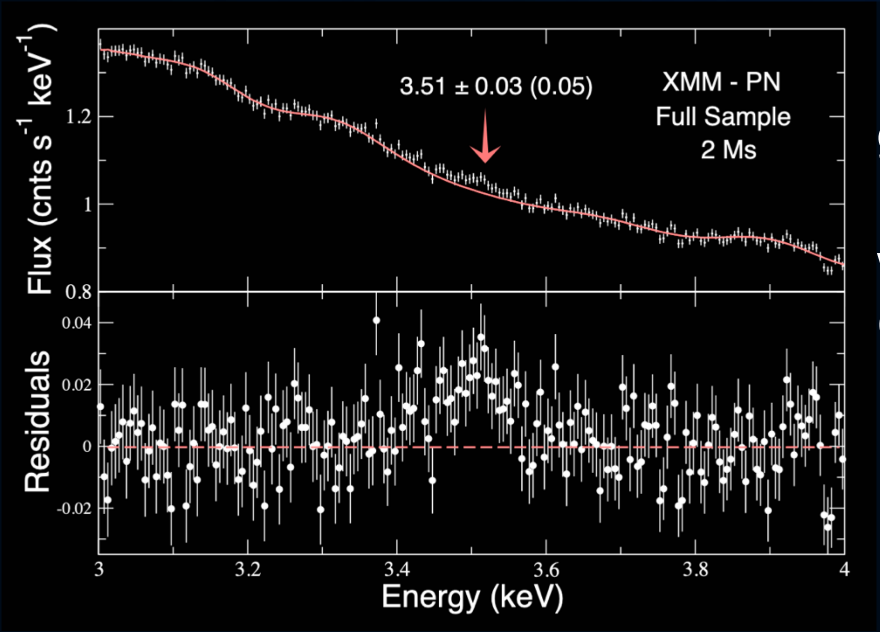


$$\chi(\chi) \longrightarrow (\ldots) \to e^+ e^-$$



Adapted from Cirelli, Fornengo, **EP**, Roach, JCAP 07 (2023) 026
See Balaji et al (2025) for eROSITA

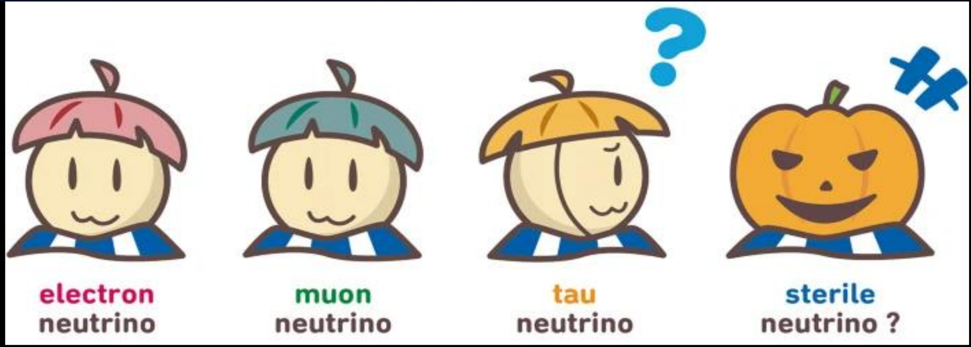
3.5 keV line? & Sterile Neutrinos



In 2014 two independent groups reported an unidentified line at 3.5 keV with XMM-Newton and Chandra in clusters and M31

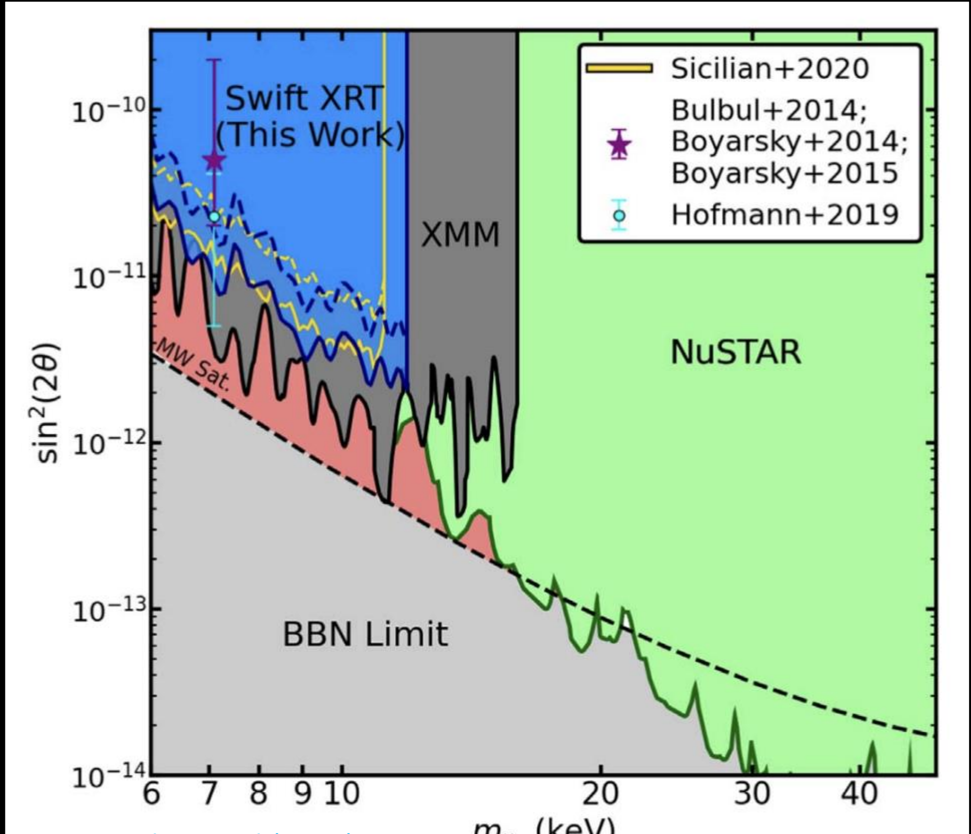
Boyarsky et al (2014)

Bulbul et al (2014)

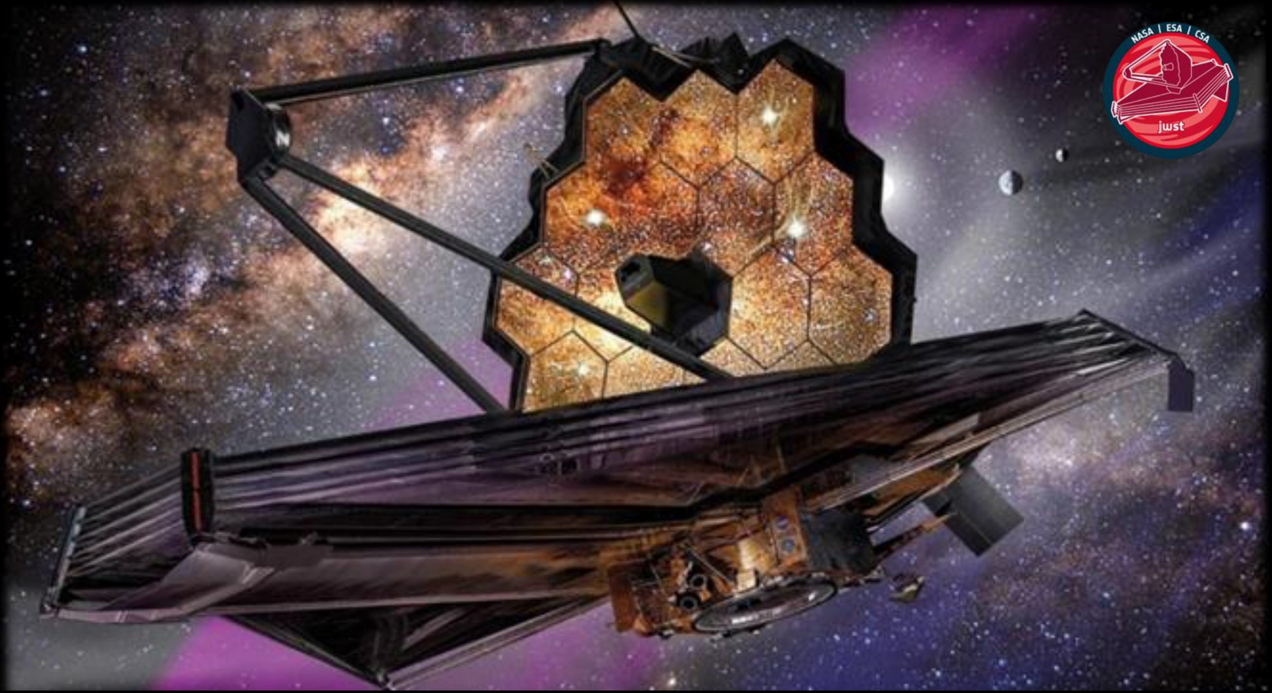


$$\nu_s \longrightarrow \nu + \gamma \qquad \text{with } m_{\nu_s} = 7 \text{ keV}$$

- ❑ Atomic lines (e.g. potassium, sulfur etc) — Jeltema et al (2015)
- ❑ The existence of the line is highly disputed — Dessert et al (2023)
- ❑ Excluded (except Shi-Fuller mechanism with large lepton asymmetry) — Vogel et al (2025), Akita et al (2025)



Sicilian et al (2022)

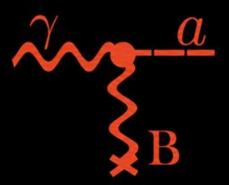


Axion searches with infrared and optical light

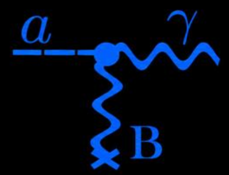
See Fuminobu Takahashi’s talk on Axion Cosmology

Axion Searches with Infrared & Optical Telescopes

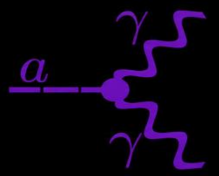
1. Primakoff production in stars: $\gamma \to a$

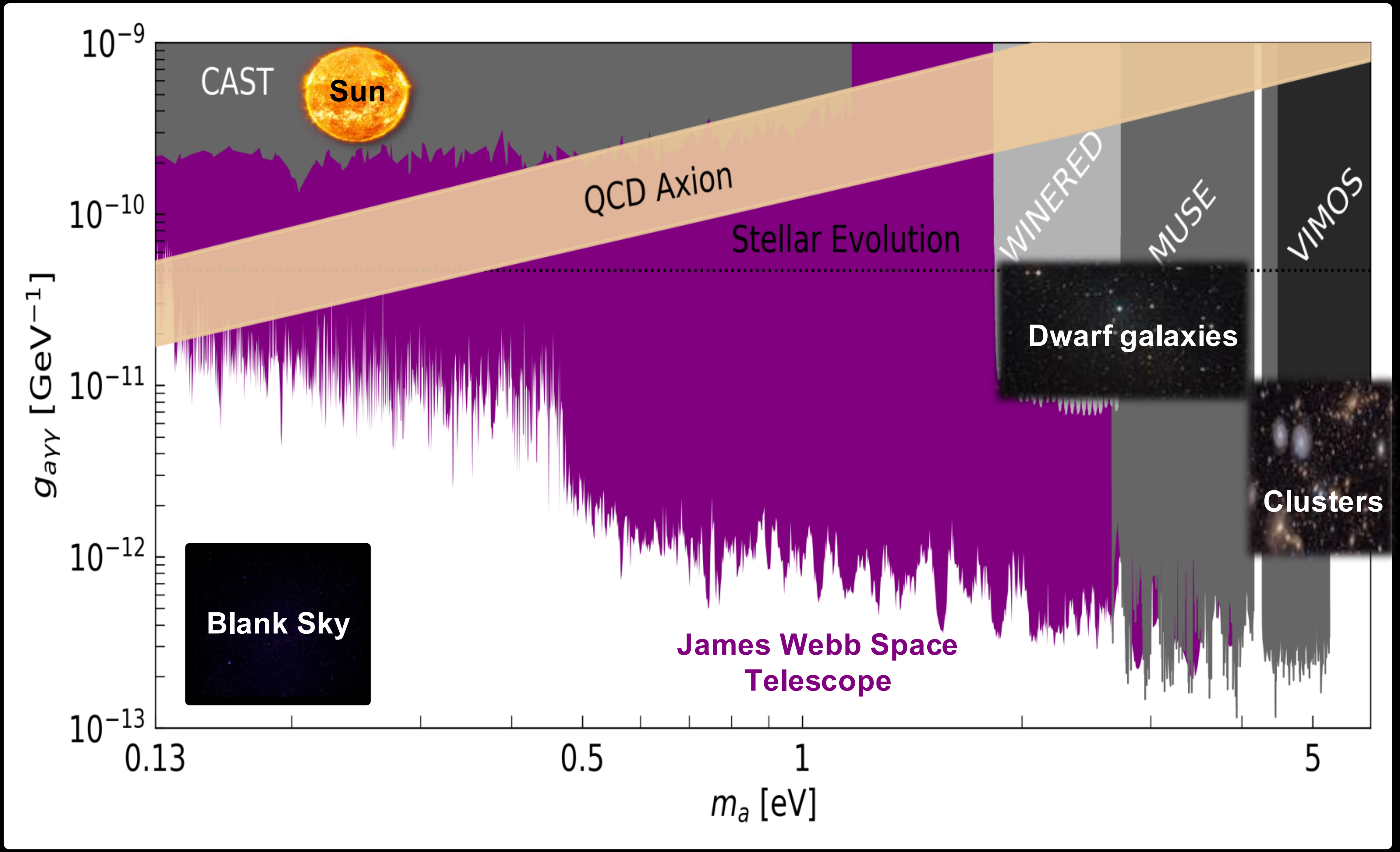


2. Conversion $a \leftrightarrow \gamma$ in lab and astro B-fields



3. Axion decay $a \to \gamma\gamma$

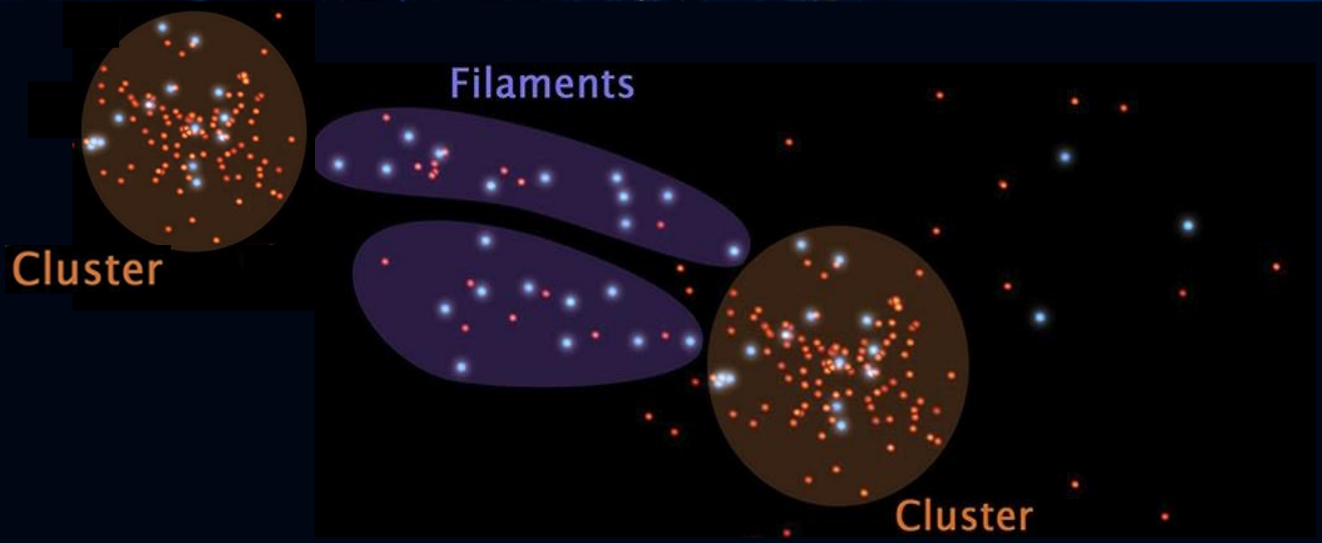


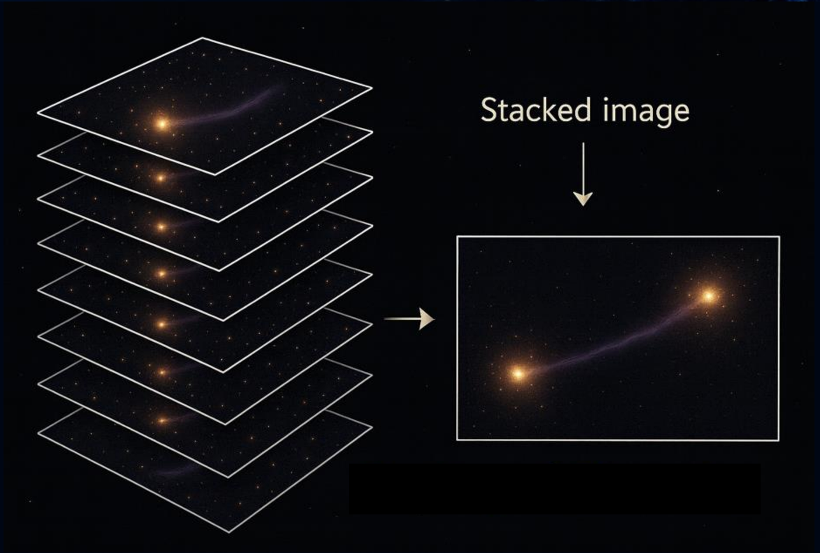


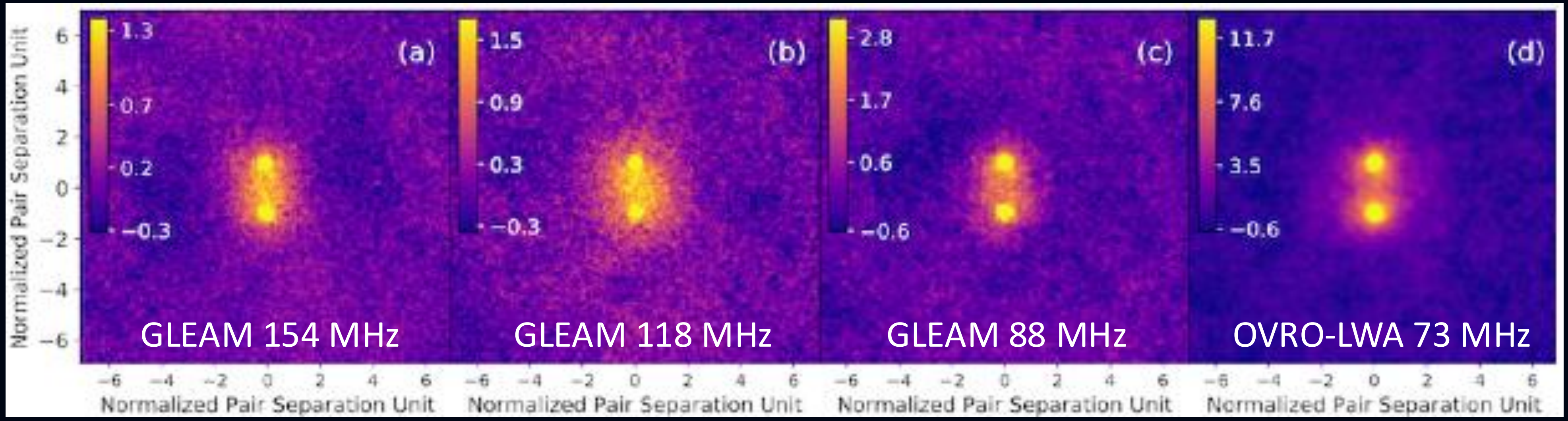
Adapted from **EP (2025)**

Radio searches in the cosmic web

Dark matter searches with the cosmic web





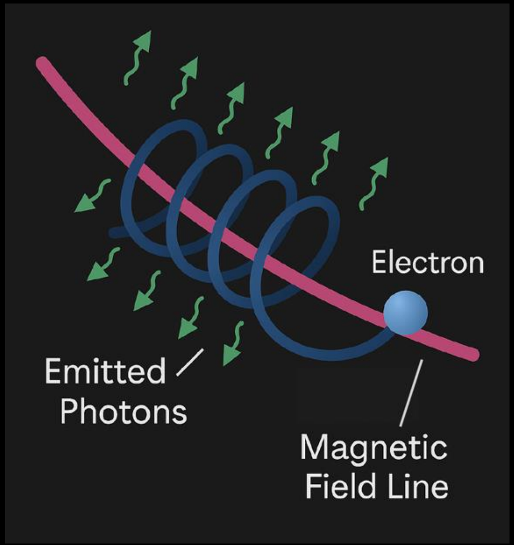


Vernstrom et al (including **EP**), MNRAS 505 (2021) 3, 4178-4196

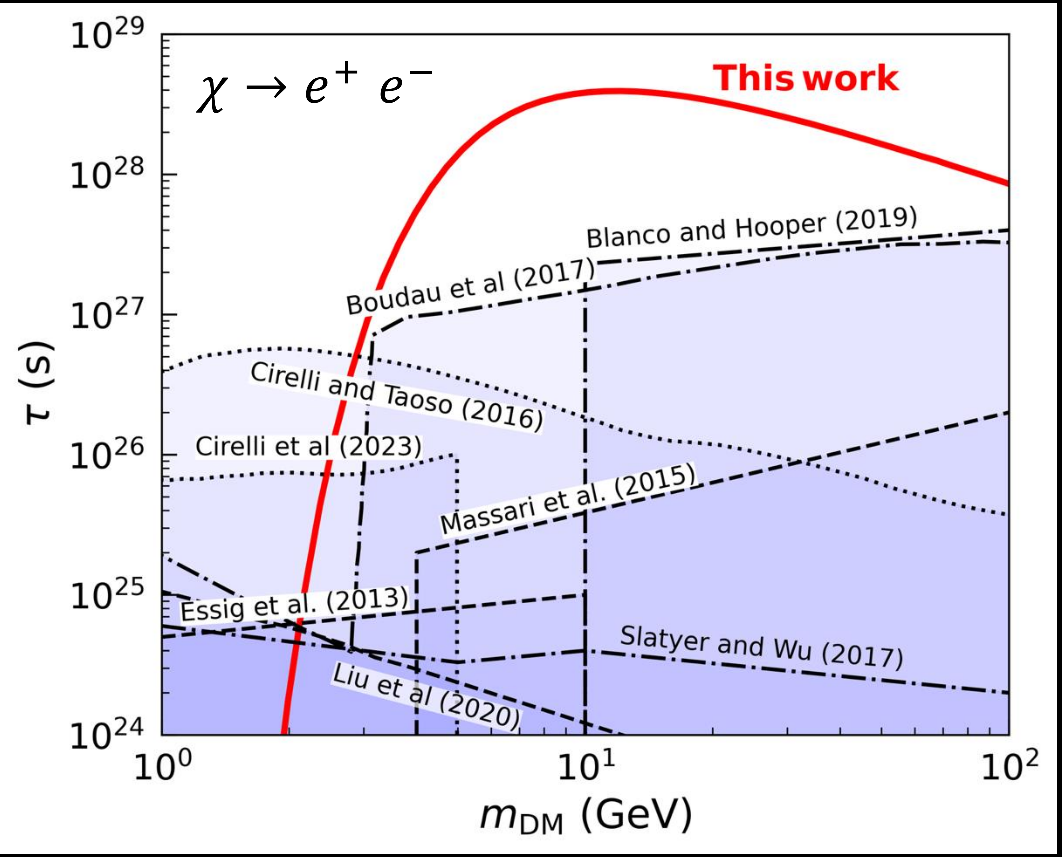
Dark matter searches with the cosmic web

$\chi \to e^+ e^-$

Synchrotron radiation



Why haven't we observed this signal elsewhere?



$m_{\rm DM} = 30$ GeV

$\tau = 2 \times 10^{27}$ s

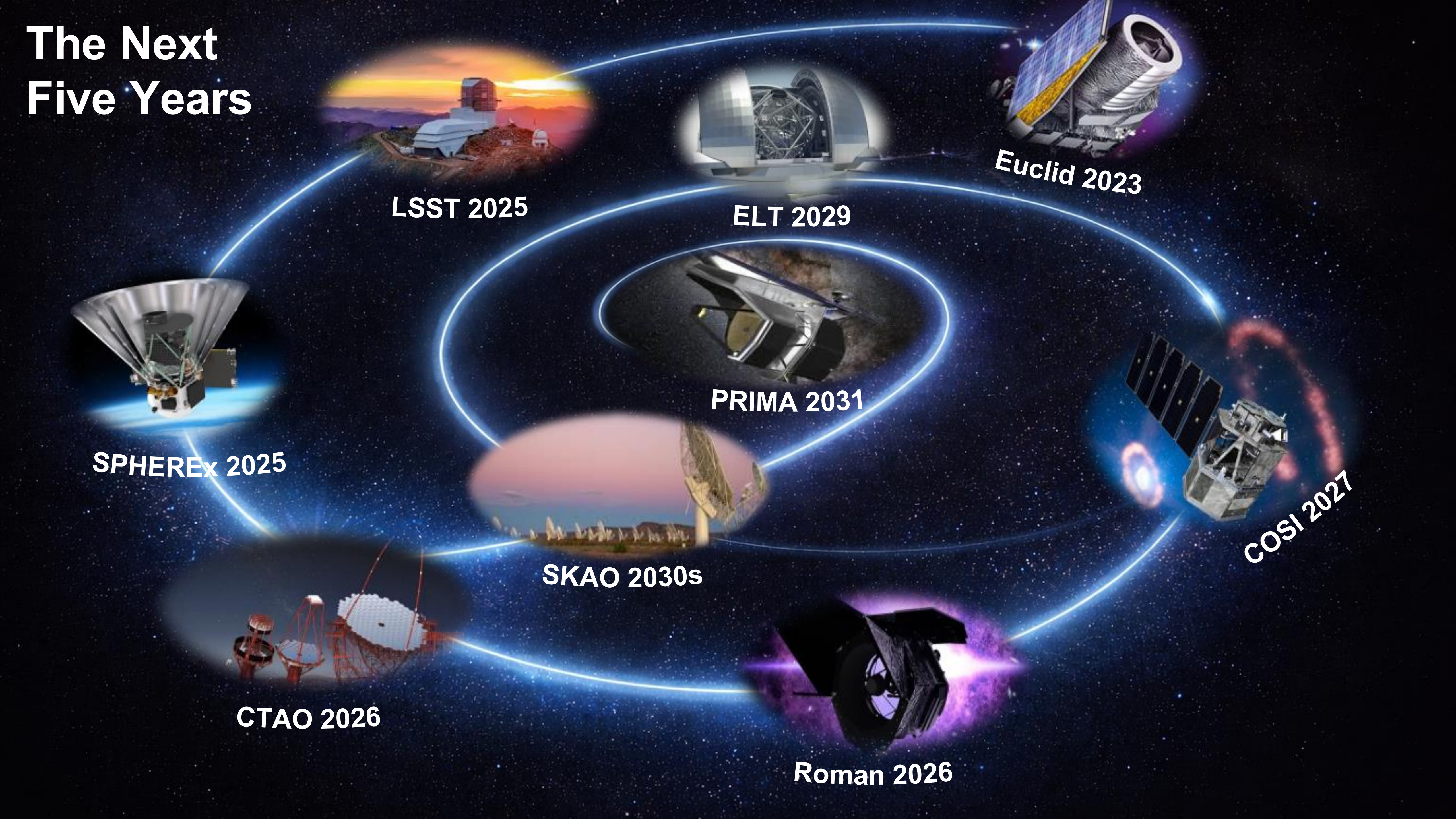
$B = 30$ nG

Mean DM density profile

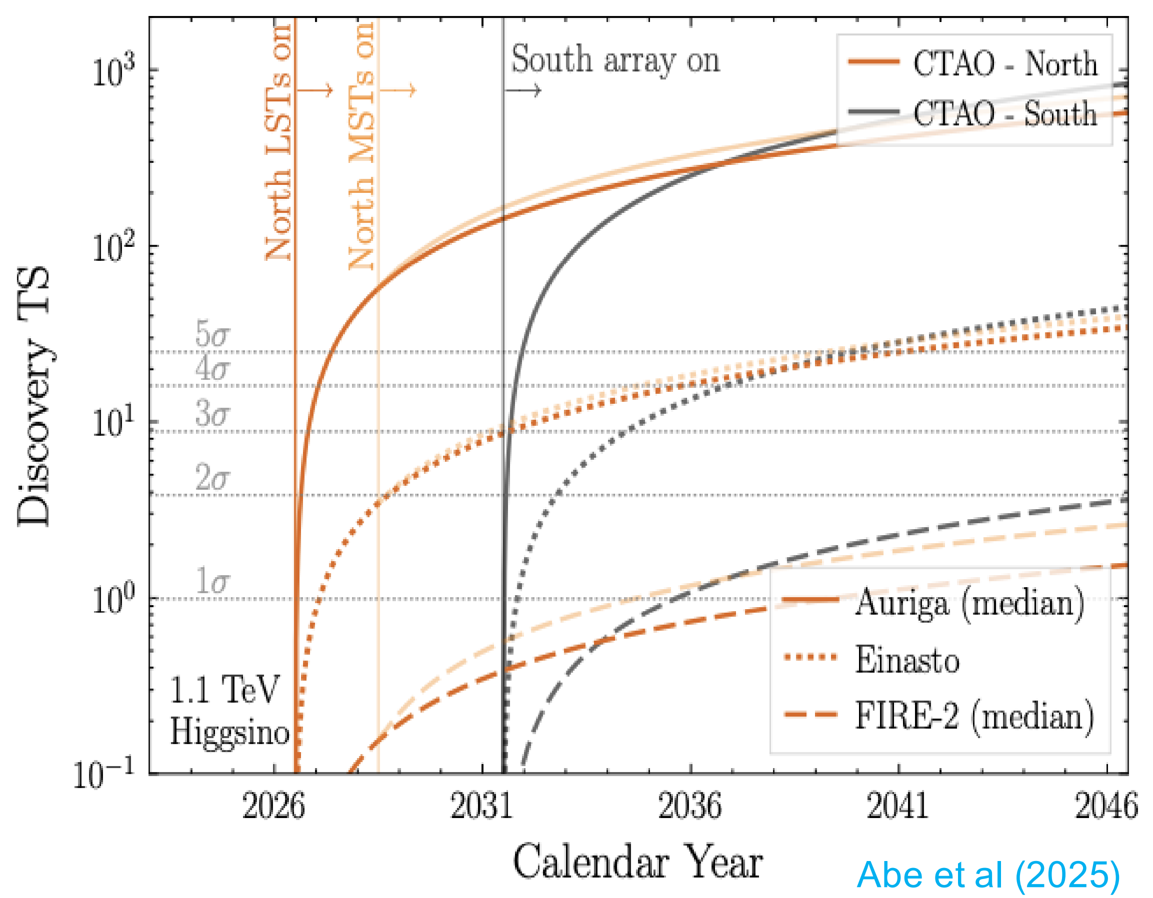
ν [MHz]	$T_b^{\rm obs}$ [K]	$T_b^{\rm DM}$ [K]
154	0.10 ± 0.04	0.10
118	0.22 ± 0.06	0.22
88	0.44 ± 0.09	0.51
73	1.1 ± 0.2	0.85

EP, Vienneau, Bozorgnia (2026)

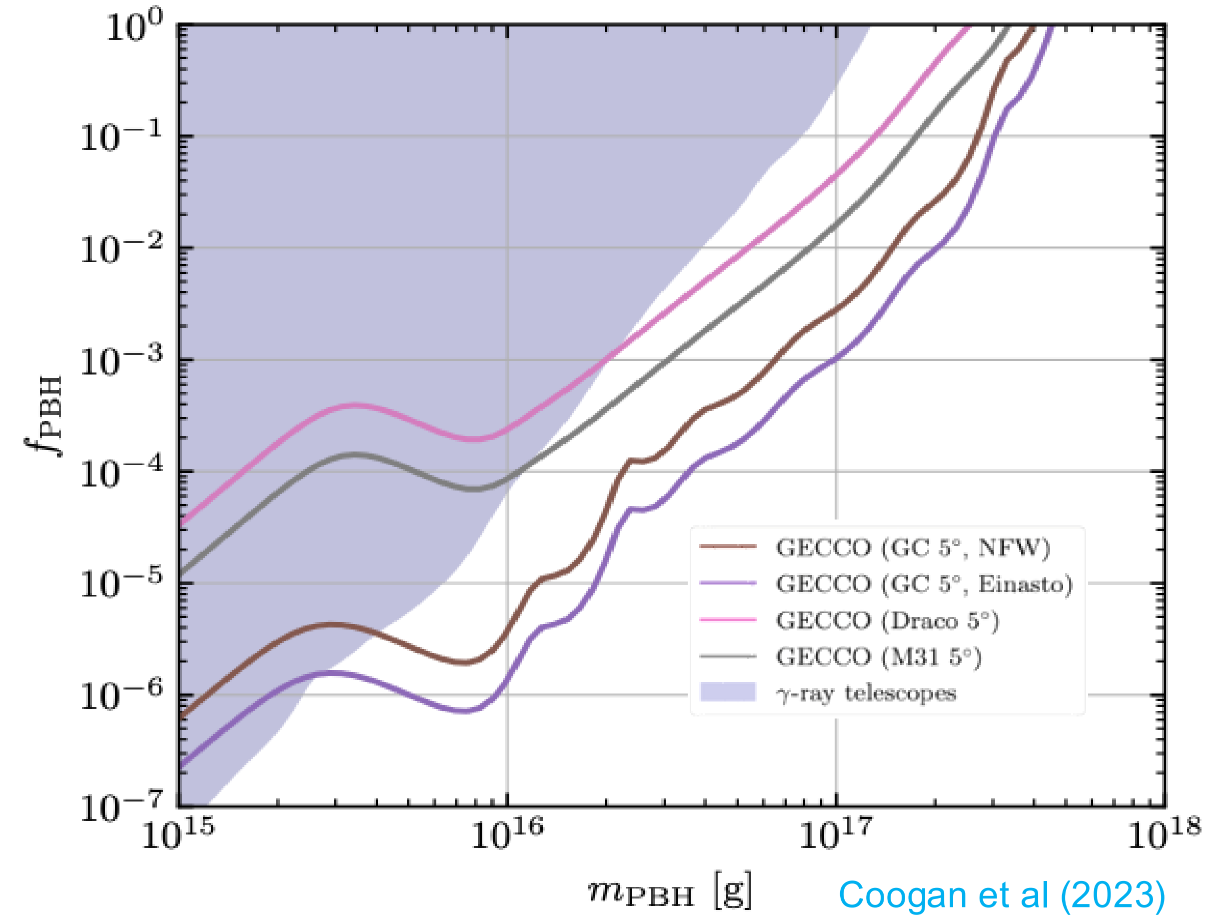
An eye toward the future


The Next Five Years
LSST 2025
ELT 2029
Euclid 2023
PRIMA 2031
SPHEREx 2025
COSI 2027
SKAO 2030s
CTAO 2026
Roman 2026

Future TeV & MeV Searches



Abe et al (2025)



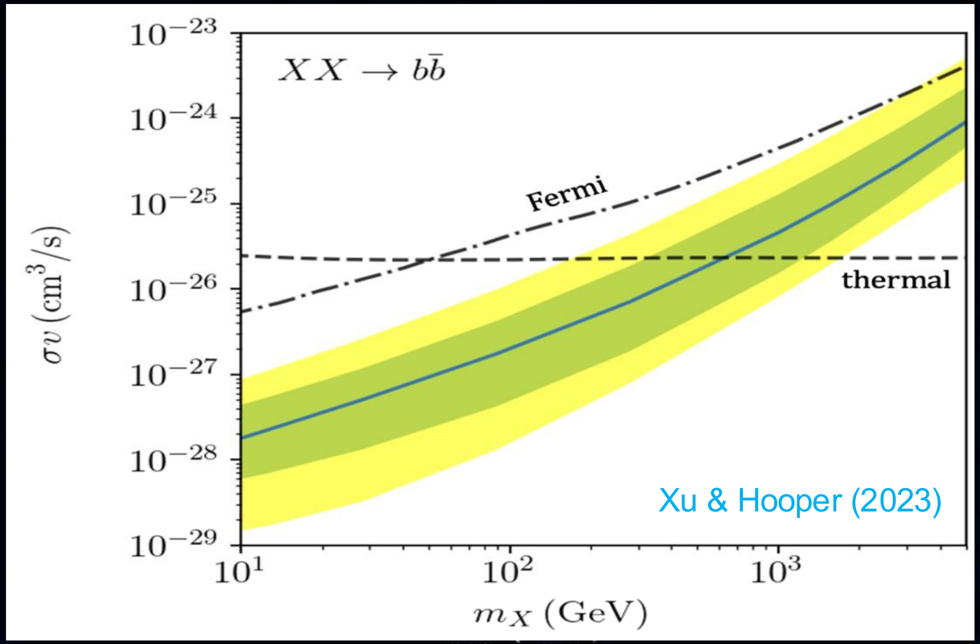
Coogan et al (2023)

See Tomislav Terzic's talk on Fundamental Physics with IACT

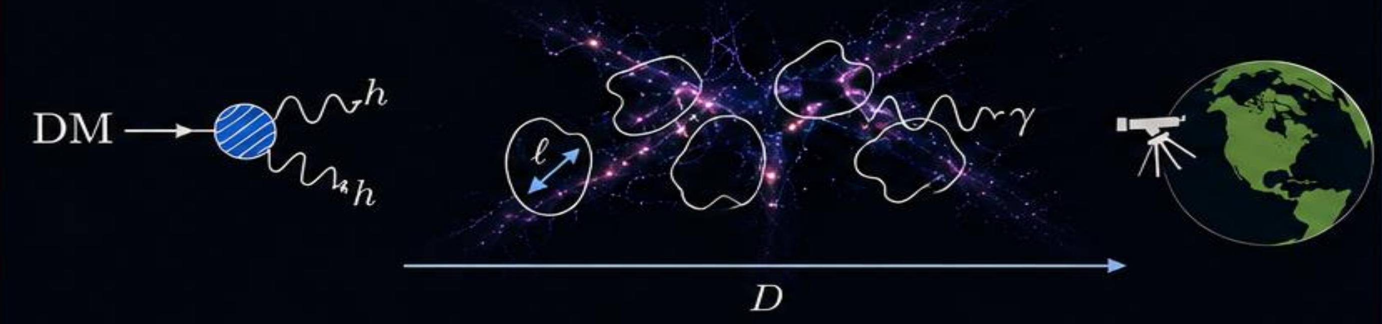
See Motoko Fujiwara's talk on WIMP paradigms

See John Tomsick's talk on MeV γ-ray astronomy and COSI

Future GeV Searches



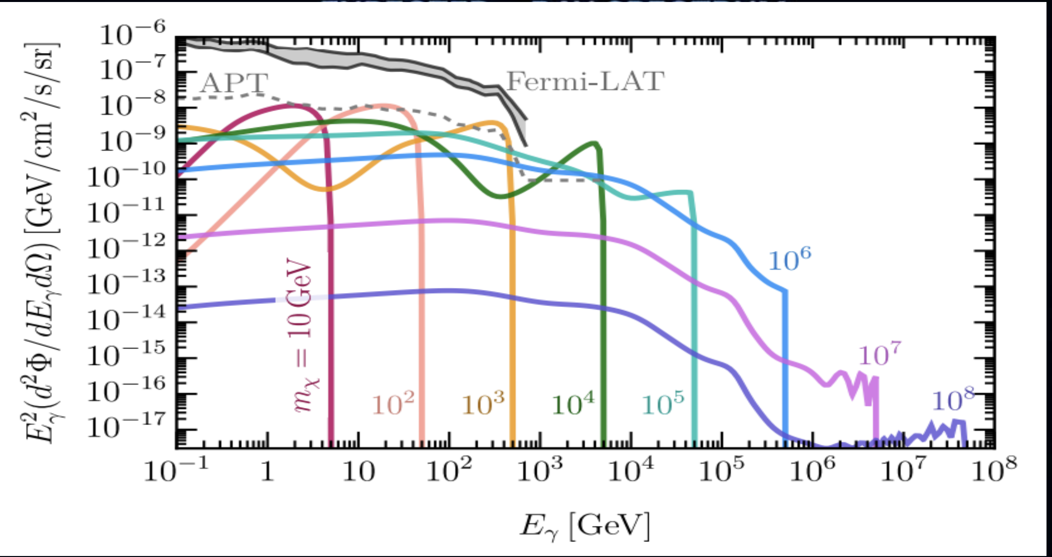
GRAVITON–PHOTON CONVERSION IN COSMOLOGICAL FILAMENTS



KEY IDEA

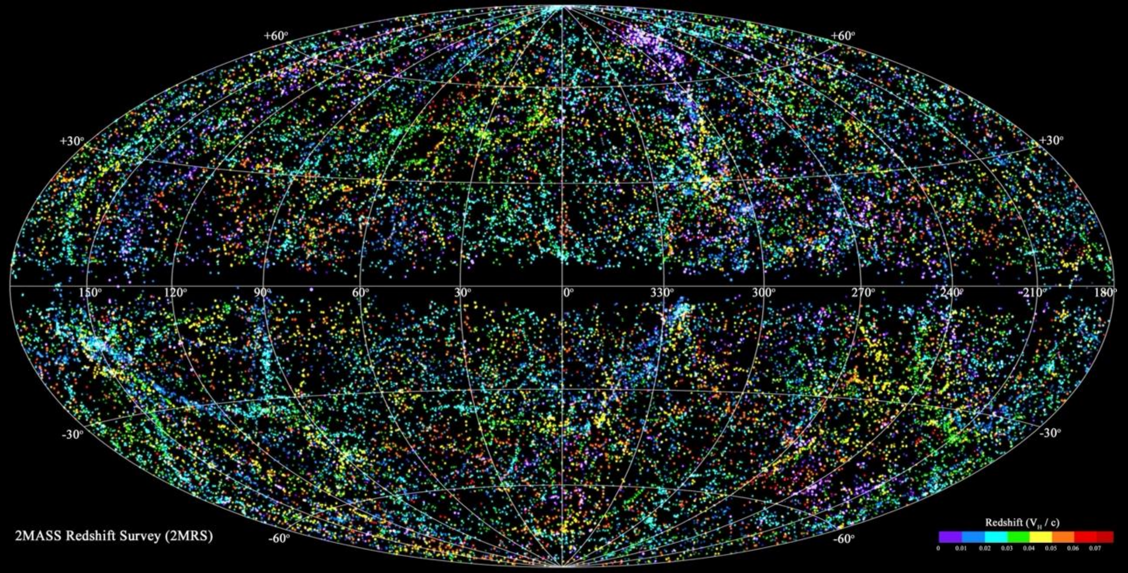
Graviton–photon conversion in cosmological filaments

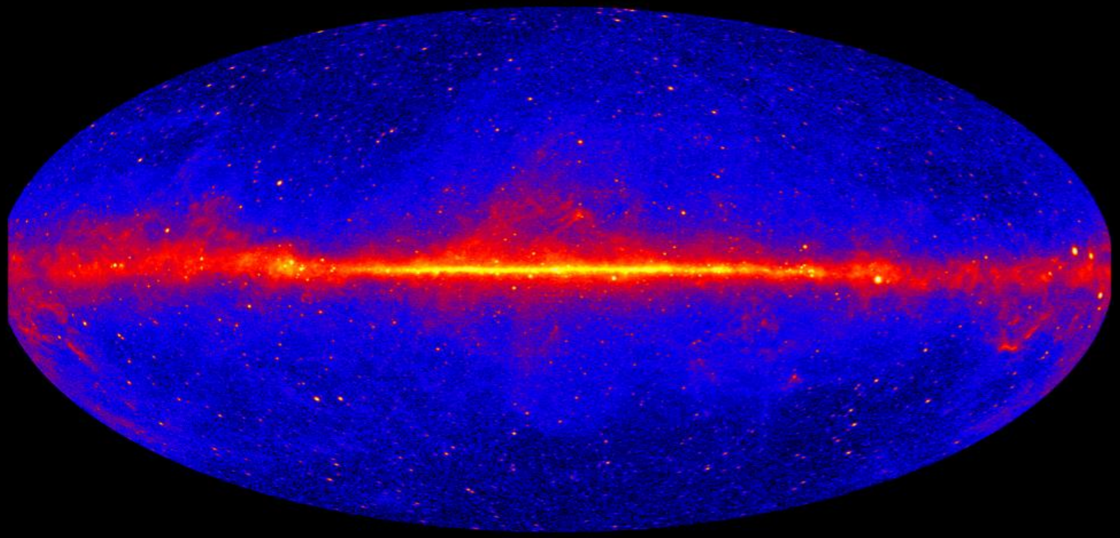
⟶ irreducible γ-ray signal



Dunsky, Krnjaic, EP (2025)

Observational Synergies





Gravitational tracers

Galaxy catalogues

Clusters catalogues

Neutral hydrogen

Weak lensing

✖

DM signals

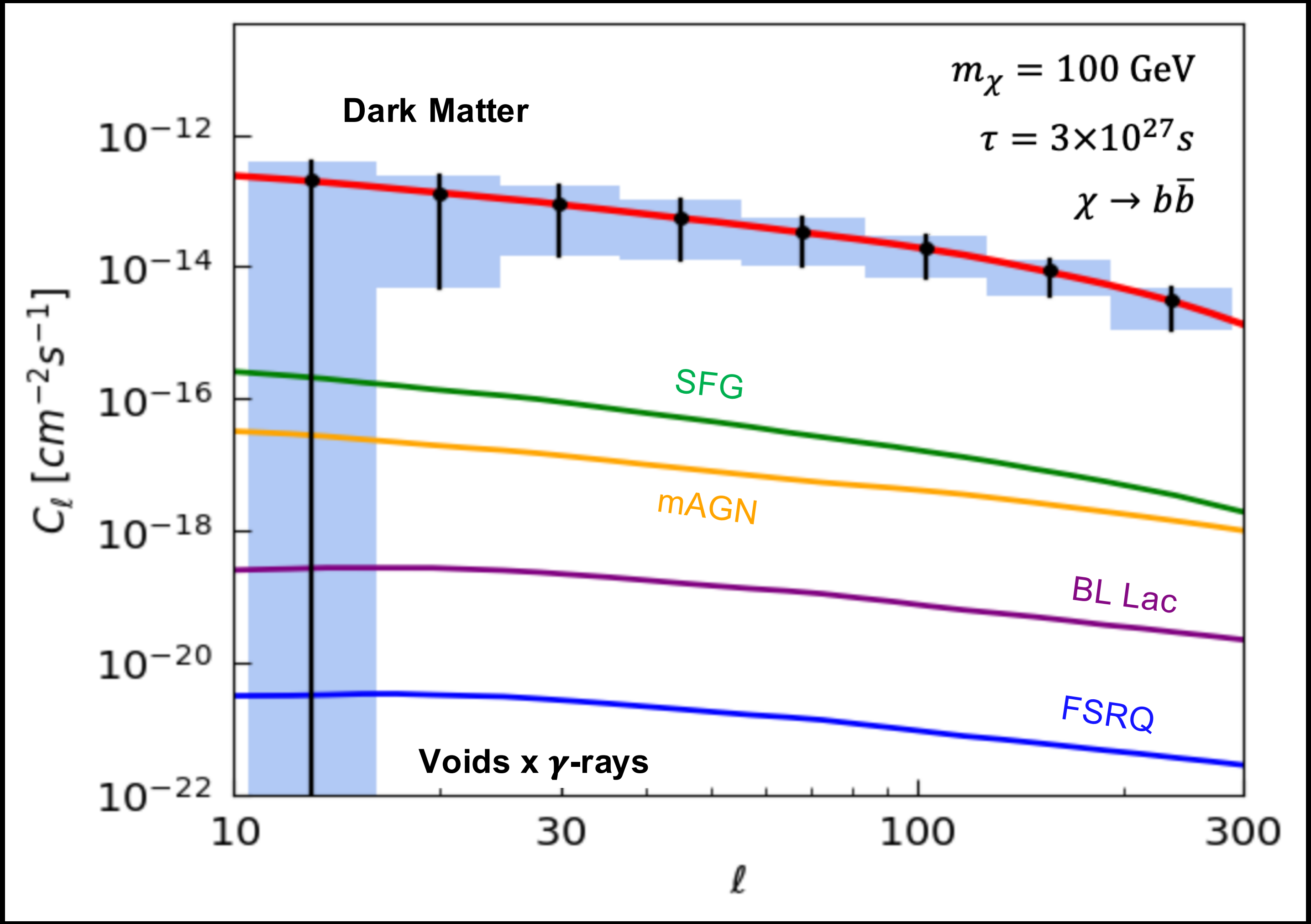
γ rays

X rays

IR emission

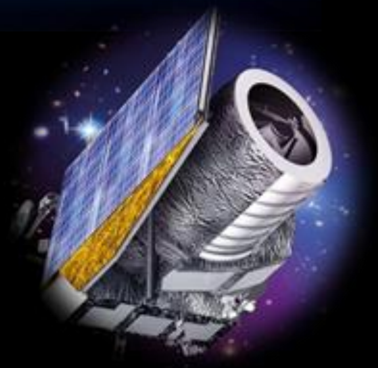
Radio waves

Observational Synergies



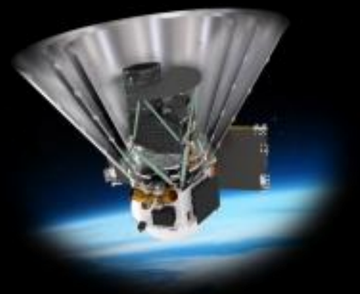
Arcari, **EP** et al (2022)

DESI 2021



Euclid 2021

Rubin 2025



SPHEREx 2025

Timely!

Roman 2026

Summary & Conclusions

1. Next-generation telescopes turn into sensitive experiments for particle physics

2. Traditional and new environments (e.g. filaments and voids) open novel windows on dark matter

3. Success requires critical cross-pollination between particle physics, cosmology, and astrophysics

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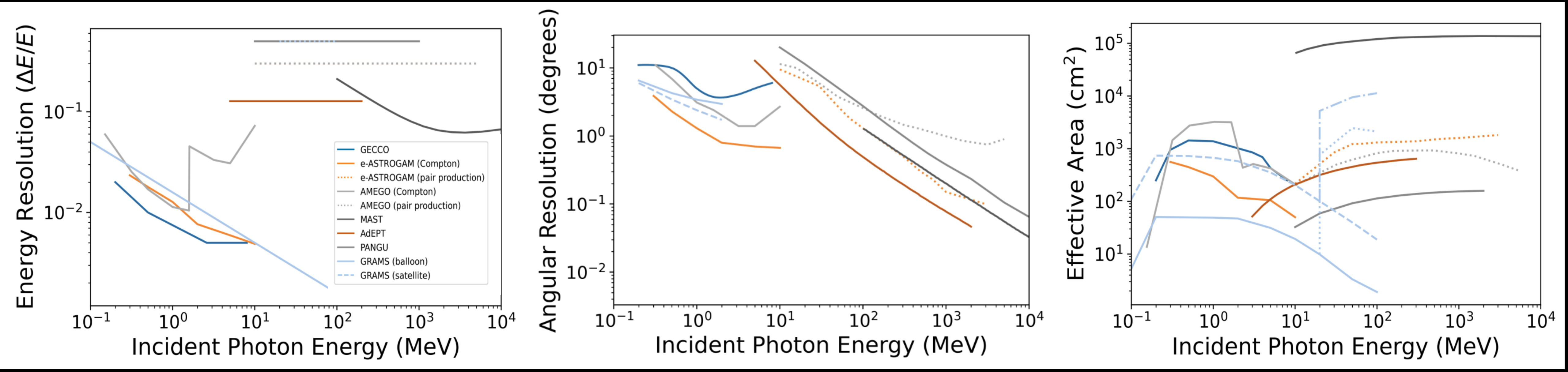
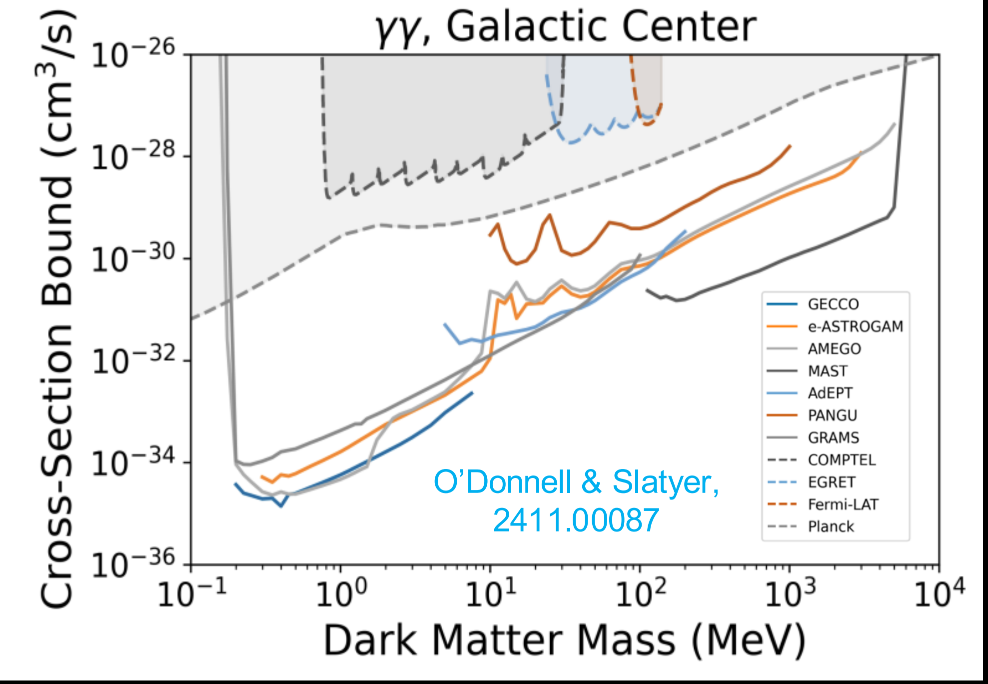
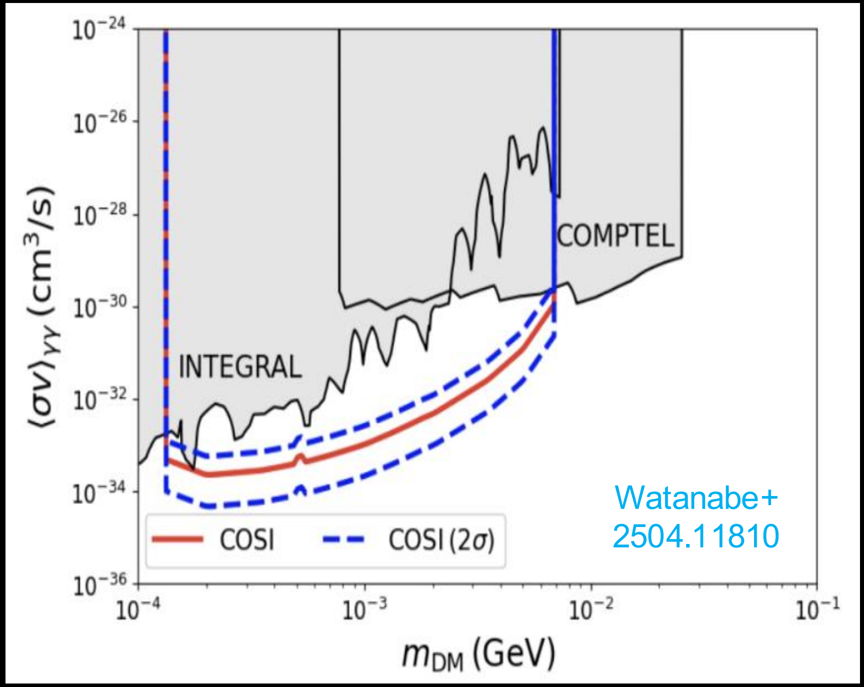
Back-Up Slides

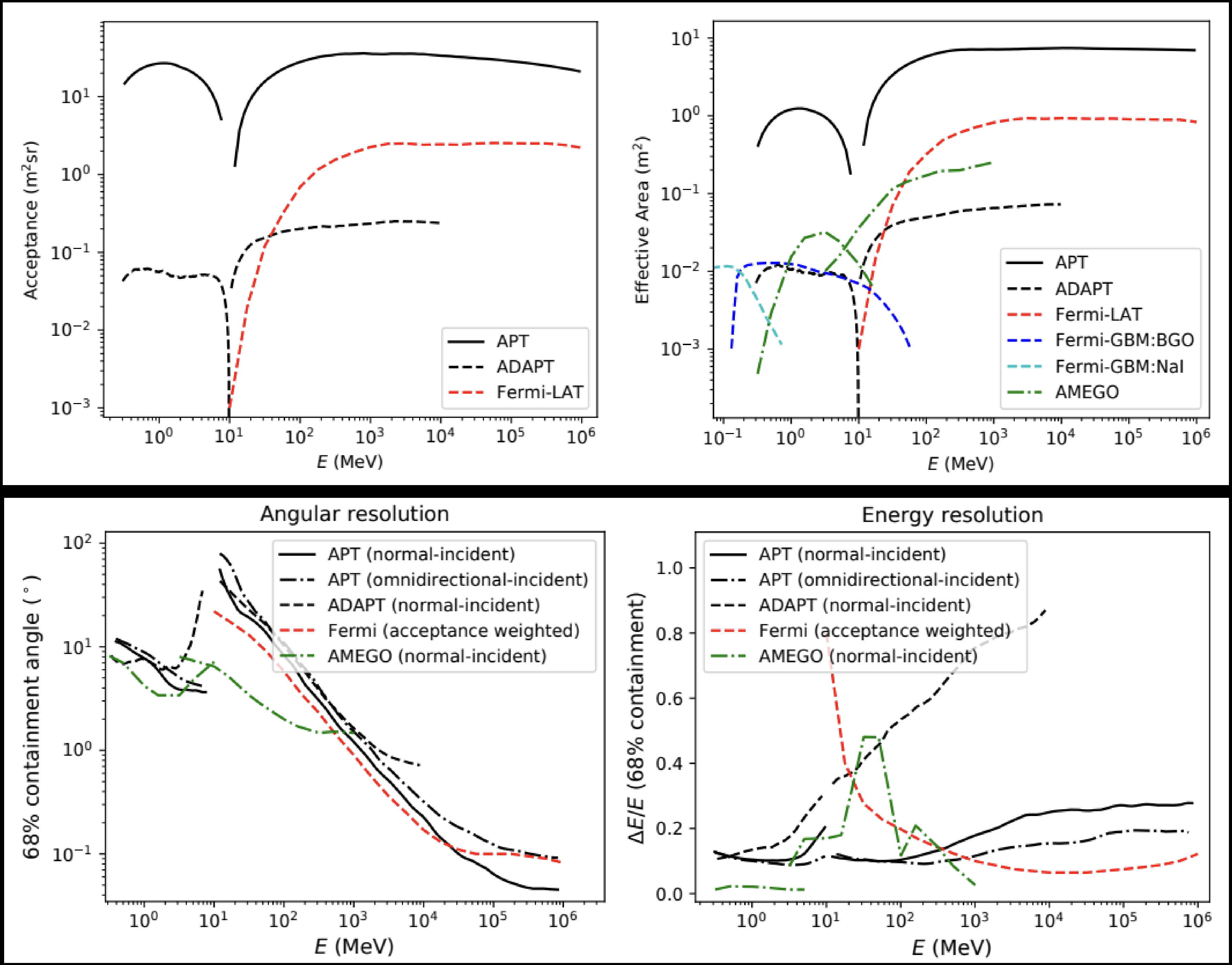
Future MeV Telescopes







APT Performance



S. Alnussirat et al., “The Advanced Particle-astrophysics Telescope: Simulation of the Instrument Performance for Gamma-Ray Detection,” PoS ICRC2021 (2021) 590.

Experiments	Wavelength	Sky Coverage	Angular Resolution
Vera Rubin (LSST)	0.3 – 1.0 μm Optical	40-45%	0.7”
Euclid	0.55 – 2.0 μm Optical + NIR	35%	0.2”
Roman	0.5 – 2.3 μm Optical + NIR	5%	0.1”
SPHEREx	0.75 – 5 μm NIR	100%	6”
JWST	0.6 – 28 μm NIR + mid-IR	< 1%	0.06”

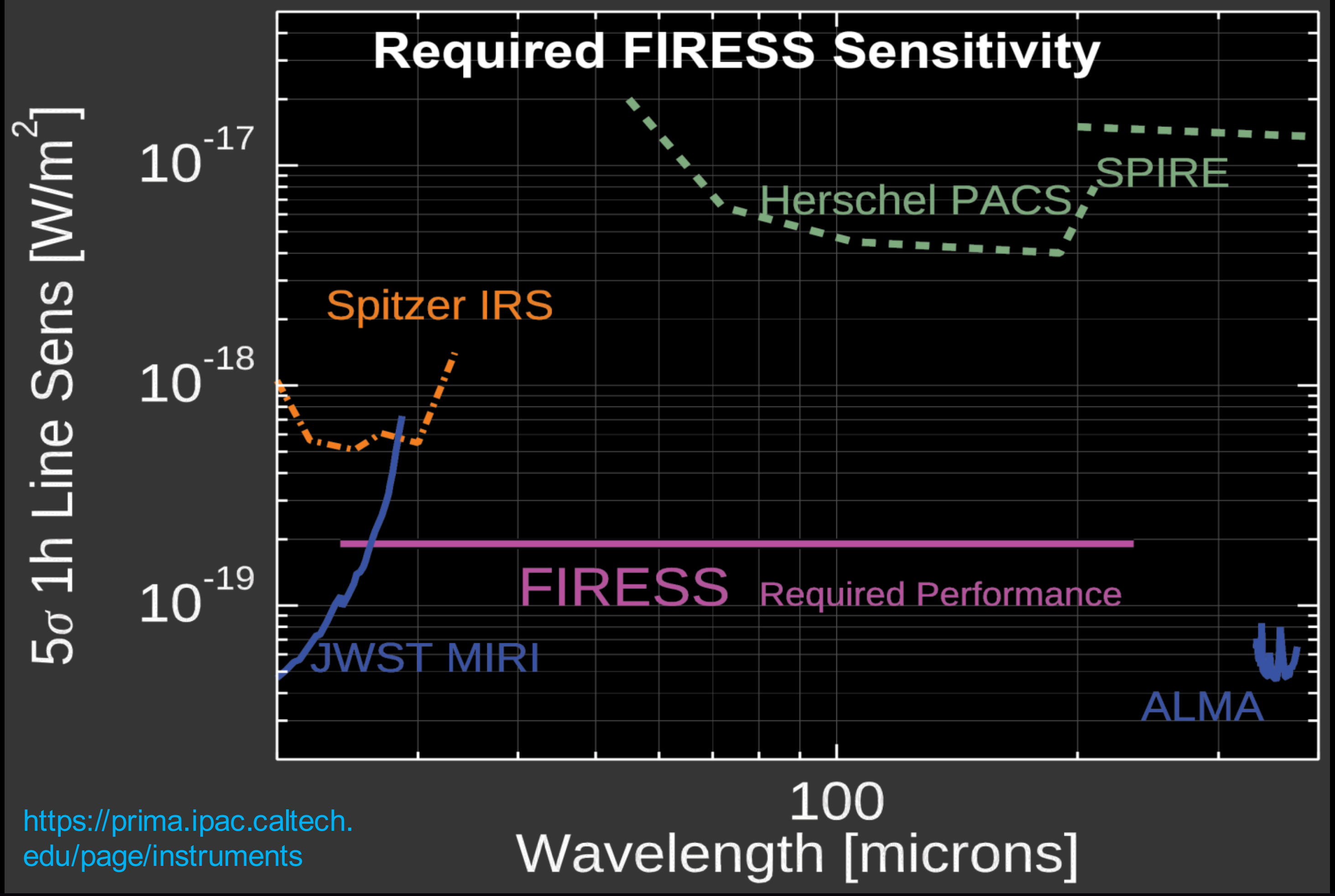
Resolution Hierarchy:

JWST > Roman > Euclid > LSST >> SPHEREx

Sky Fraction Hierarchy:

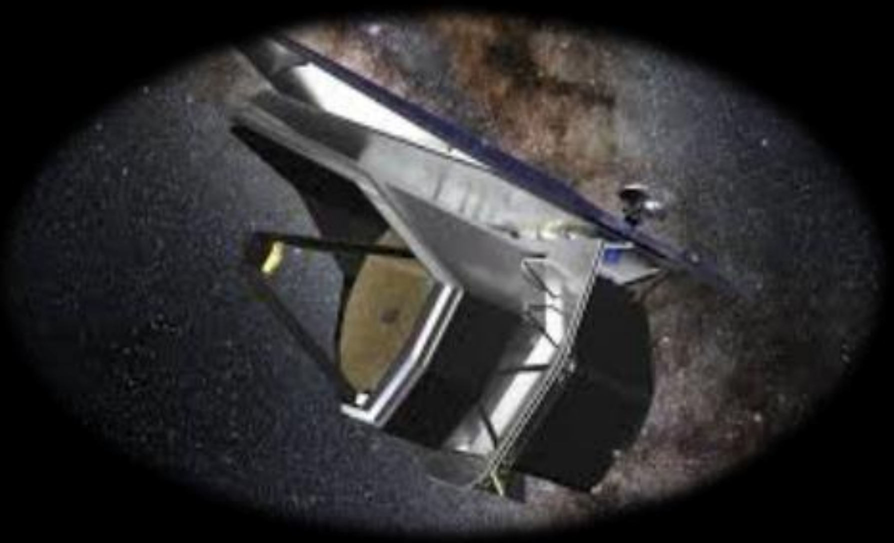
SPHEREx > LSST ~ Euclid >> Roman >> JWST

These experiments span complementary regimes:
From all-sky low resolution (SPHEREx) to ultra-deep and small sky coverage (JWST)



https://prima.ipac.caltech.edu/page/instruments

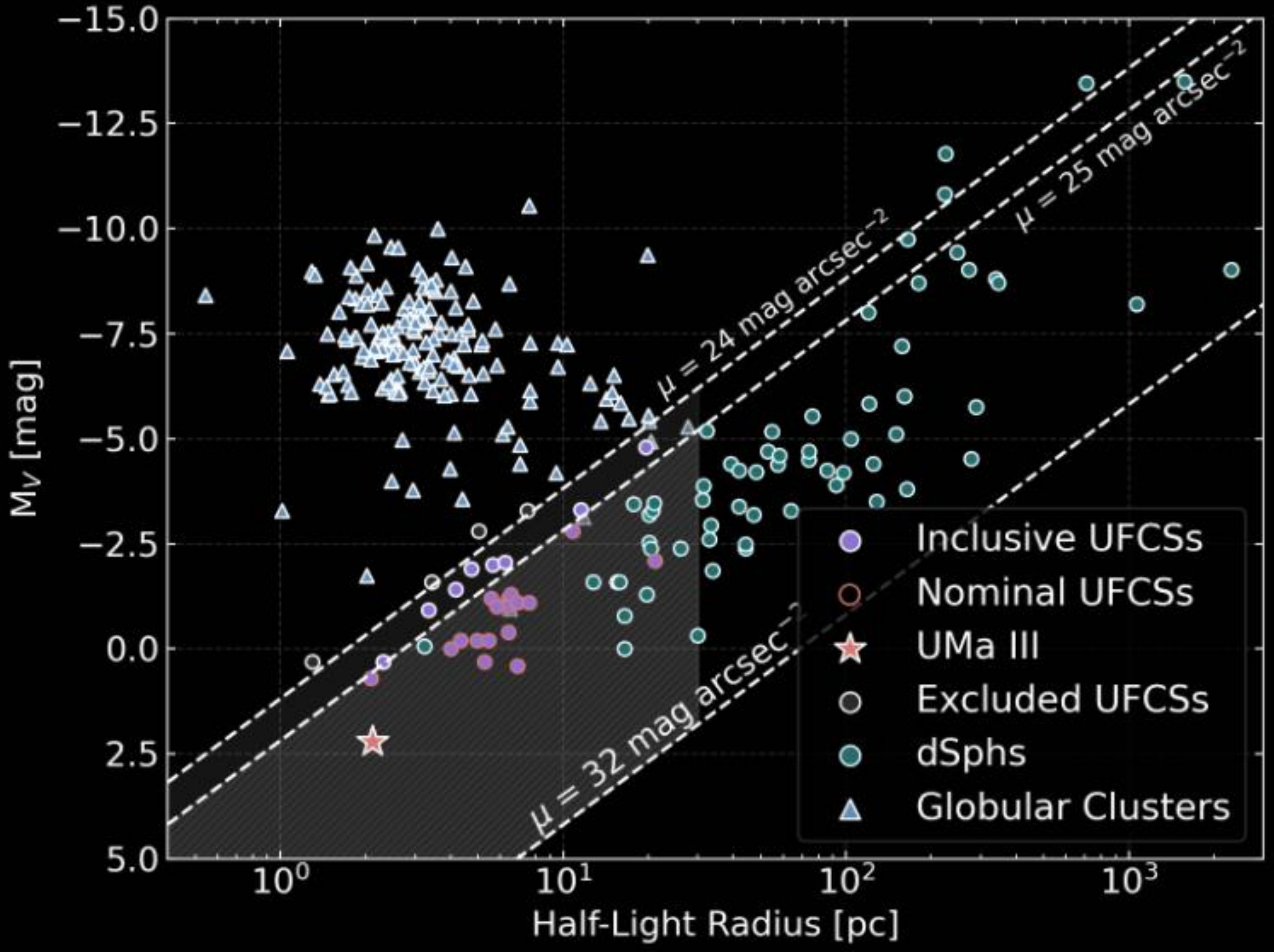
PRIMA



Parameter	Band 1	Band 2	Band 3	Band 4
Spectral range [μm]	24–43	42-76	74–134	130–235
Resolving power (low-res)	95–150	85–120	90–125	95–130
Resolving power (FTM)	20,000–11,000	12,000–6,500	6,600–4,000	3,800–2,100
Array format	24 spatial pixels × 84 spectral pixels			
Pixel size ["]	7.6	7.6	12.7	22.9

PRIMA's Far Infrared Enhanced Survey Spectrometer (FIRESS) offers multi-mode spectroscopy capable of both area mapping as well as dedicated point source observations. At the heart of FIRESS are four slit-fed grating spectrometer modules which are logarithmically spaced in wavelength and combine to cover the full 24-235 μm band. In addition, a Fourier Transform Module (FTM) can be inserted in the light path of the grating modules to produce high-resolution spectroscopy across the full wavelength band.

Dwarf Galaxies vs Stellar Clusters



Circiello et al, APJ Lett. 978 (2025) 2, L 43

Dwarf Galaxies:
extended & low luminosity

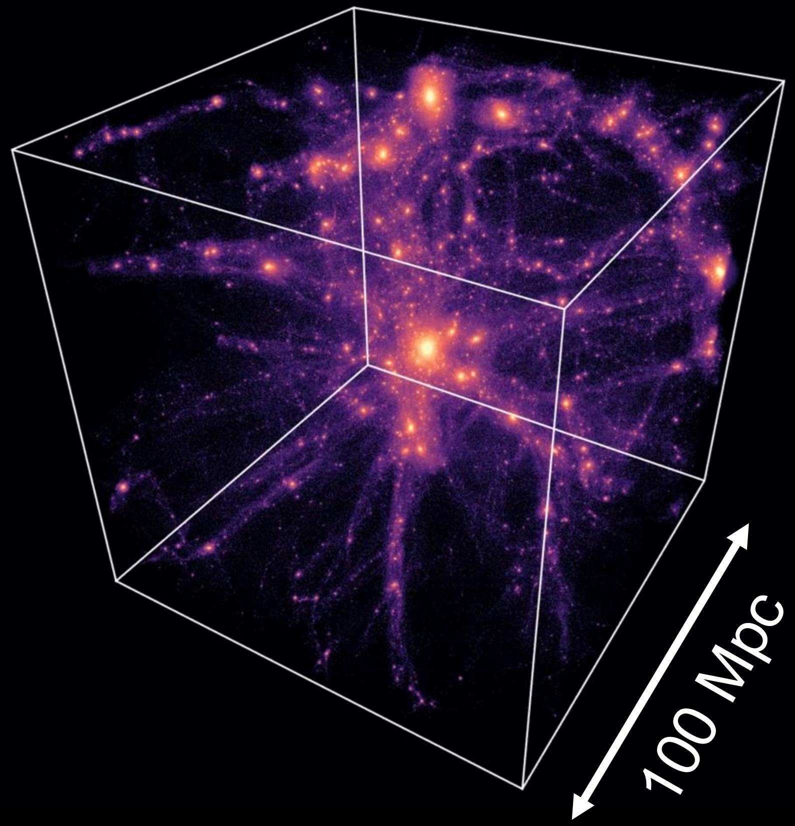
Stellar Clusters:
compact and more luminous

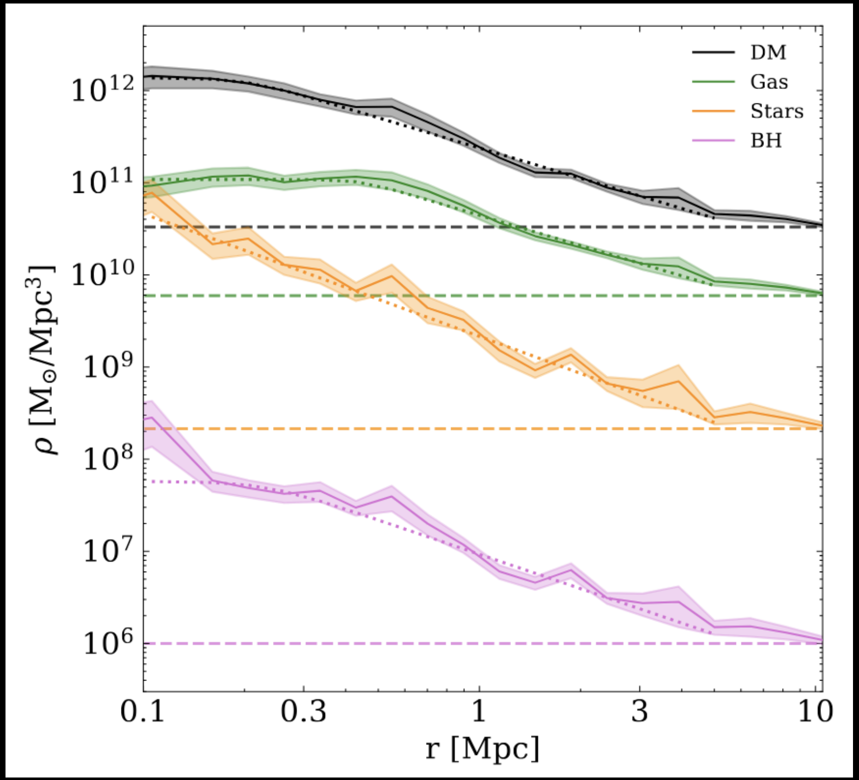
According to Cerny et al (2025), UMaIII/U1 is the least-luminous and most metal-poor Milky Way globular cluster known.

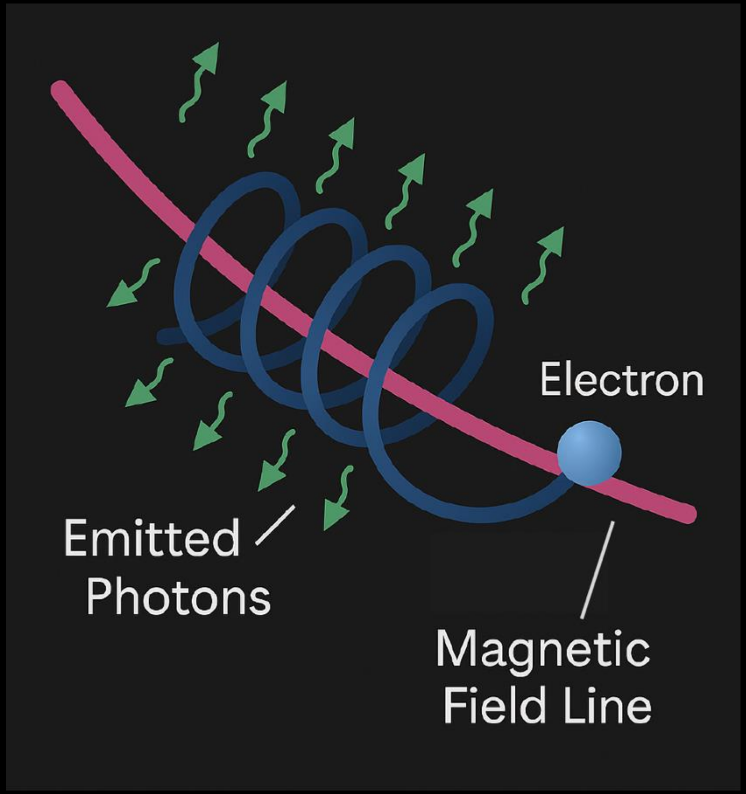
The Dark Matter Signal

$\mathrm{DM} \rightarrow e^{+}\, e^{-}$ → Synchrotron radiation


Evan Vienneau (Graduate Student, University of Alberta)







EP et al (2025b)

See also Yang, Hudson, Afshordi (2022)

Why Filaments?

Domain	B (nG)	ℓ (Mpc)	$f_{\rm vol}$	$B^2 \ell f_{\rm vol}$
Filaments	$10-100$	~ 1	$\sim 10^{-1}$	$10-10^3$
Clusters	$\sim 10^3$	$\sim 10^{-2}$	$\sim 10^{-2}$	$\sim 10^2$
Voids	$10^{-7}-10^{-4}$	~ 1	~ 1	$10^{-14}-10^{-8}$

TABLE I. Comparison of cosmological domains where graviton to photon conversion can occur. Filaments [4, 5, 28], galaxy clusters [28, 35], and voids [28, 36, 37] possess different typical magnetic fields B, coherence lengths ℓ, and volume filling fractions $f_{\rm vol}$. The contribution to the diffuse gamma-ray background from DM decays to gravitons scales with $B^2 \ell f_{\rm vol}$, which is largest for cosmic filaments.

Dunsky, Krnjaic, **EP** (2026)

Magnetic Fields in Filaments

Table 2. A selection of relevant observational upper bounds on large scale extragalactic magnetic fields within the filamentary IGM, sorted by increasing IGMF upper bound.

Upper Bound	Coherence Scale (L_c)	Redshift Range	Reference	Technique Summary
0.65 nG 1.7 nG	Jean's scale ($\lambda_j(z)$) $1/H_0$	$0 < z < 5$	Pshirkov et al. (2016)	RM vs. z
1 nG 6 nG	$1/H_0$ 50 Mpc	$0 < z < 2.5$	Blasi et al. (1999)	RM vs. z
4 nG	$L_c/\lambda_j(z=0) \leq 1000$	Unknown[5]	O'Sullivan et al. (2020)	ΔRM between adjacent sources
21 nG	~Gpc[6]	$z \sim 0.1$	Ravi et al. (2016)	RRM from FRB 150807
27 nG - 44 nG	2.5 Mpc - 0.5 Mpc	$0.1 < z < 0.5$	This paper	RRM cross-correlation
30 nG	$\theta = 1°$[7]	$z < 0.048$	Brown et al. (2017)	Synchrotron cross-correlation
30 nG - 60 nG	2 Mpc	$< z >= 0.14 \pm 0.01$	Vernstrom et al. (2021)	Statistically Stacking Filaments
30 nG - 1980 nG	1 - 4 Mpc	$0 < z < 0.57$	Vernstrom et al. (2017)	Synchrotron cross-correlation
37 nG	1 Mpc	$0 < z < 1$	Vernstrom et al. (2019)	ΔRM between adjacent sources
250 nG	~10 Mpc	$0.095 < z < 0.142$	Locatelli et al. (2021)	Non-detection of filament accretion shocks
300 nG	300 kpc	$z \sim 0.34$	O'Sullivan et al. (2019)	Observed intervening filament
300 nG	0.5 Mpc	$0.0304 < z < 0.0414$[8]	Xu et al. (2006)	RM correlation with galaxy counts

Amaral et al, MNRAS 503 (2021) 2, 2913-2926

$$B \sim O(1 - 1000)\ nG$$

Axion Decay Signal

Emission rate $\Gamma_\gamma = \frac{1}{\tau} = \frac{g_{a\gamma\gamma}^2 \, m_a^3}{64\pi}$

$$\frac{d\phi_a}{dE\,d\Omega} = \frac{\Gamma_\gamma}{4\pi \, m_a} \frac{dN}{dE} D$$

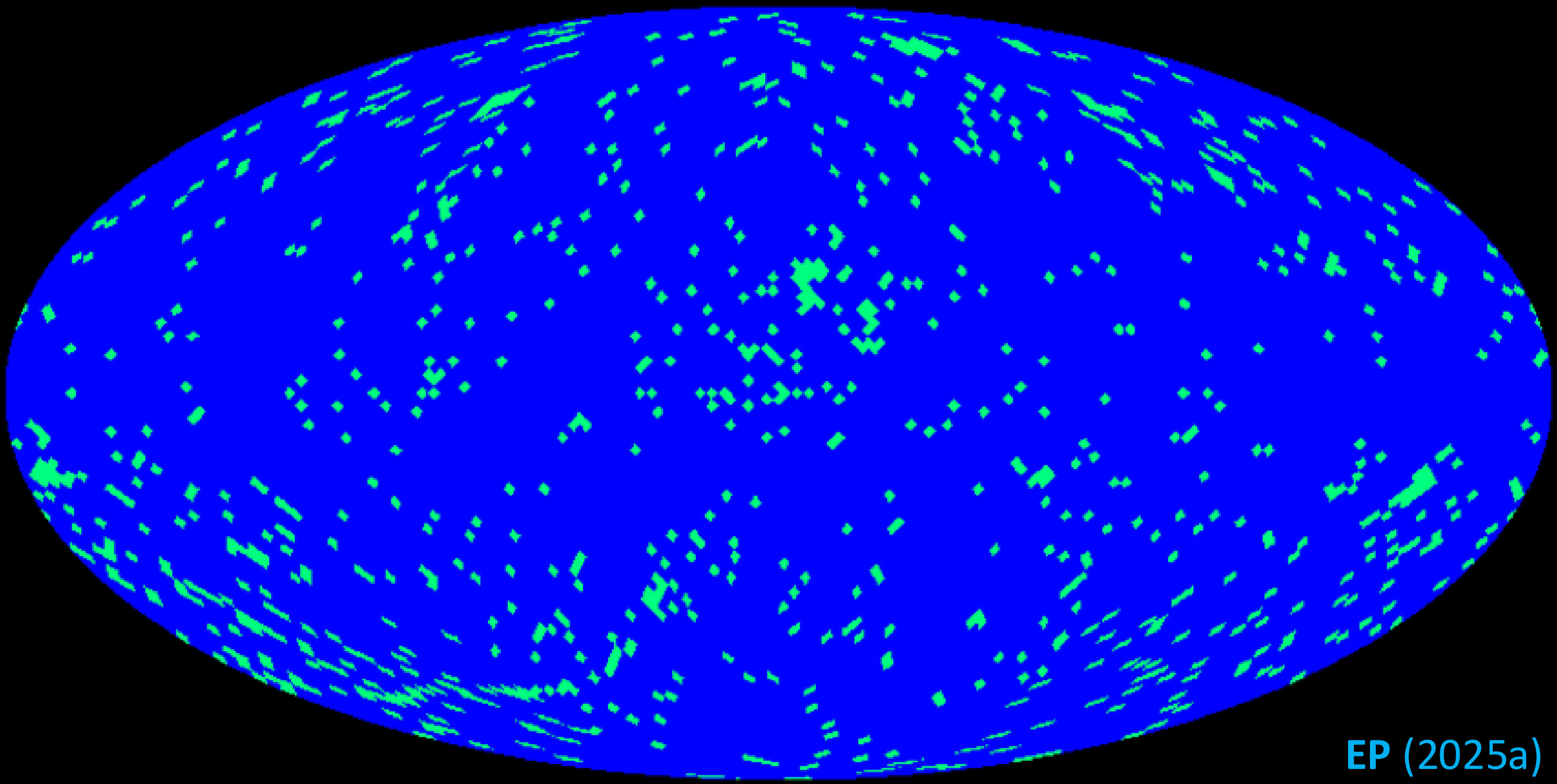
Axion mass

Emission spectrum

D-factor $D(\theta) = \int ds \, \rho\big(r(s,\theta)\big)$

$$\rho_\odot = 0.3 \text{ GeV/cm}^3$$

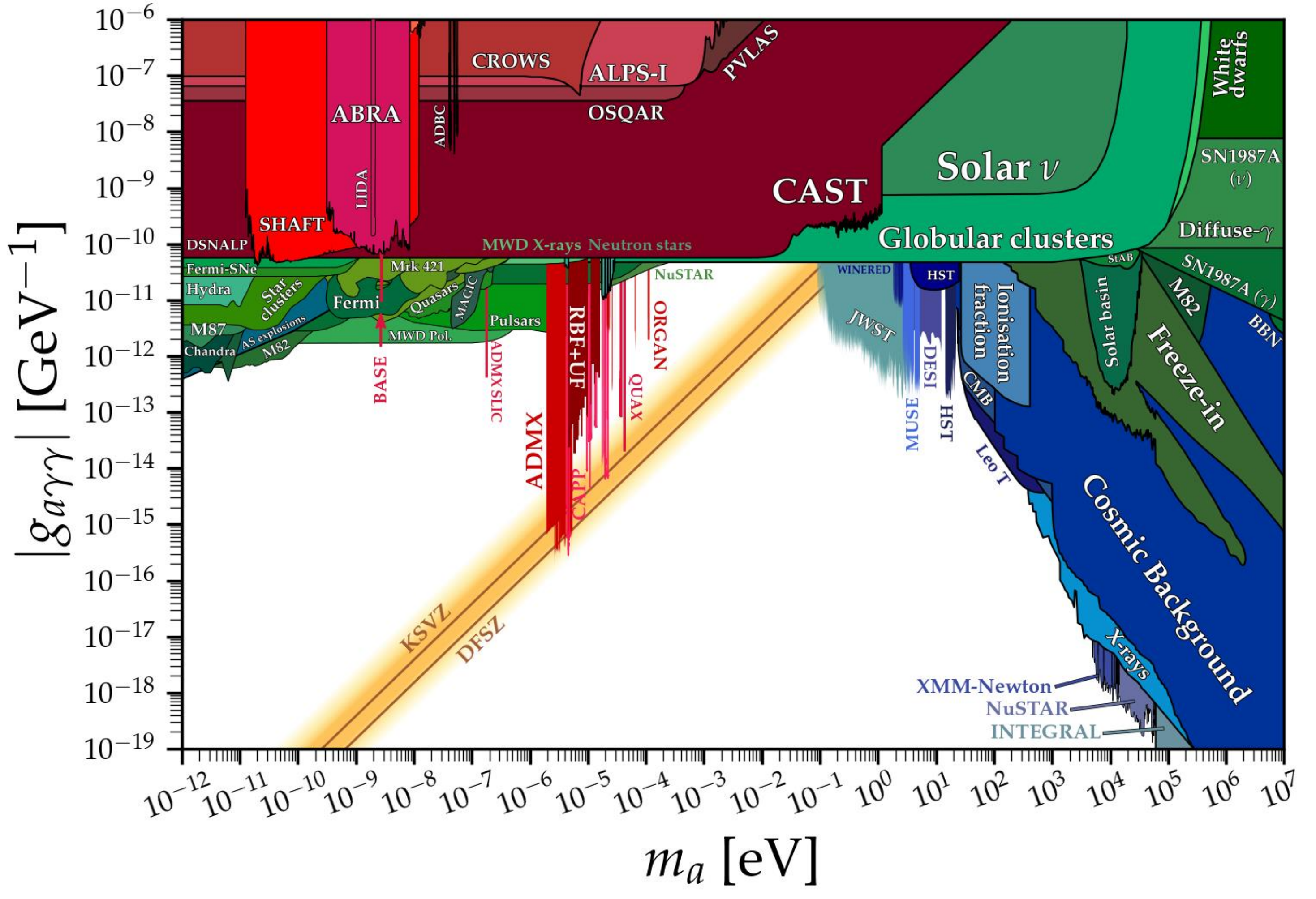
Enhanced JWST Dataset



EP (2025a)

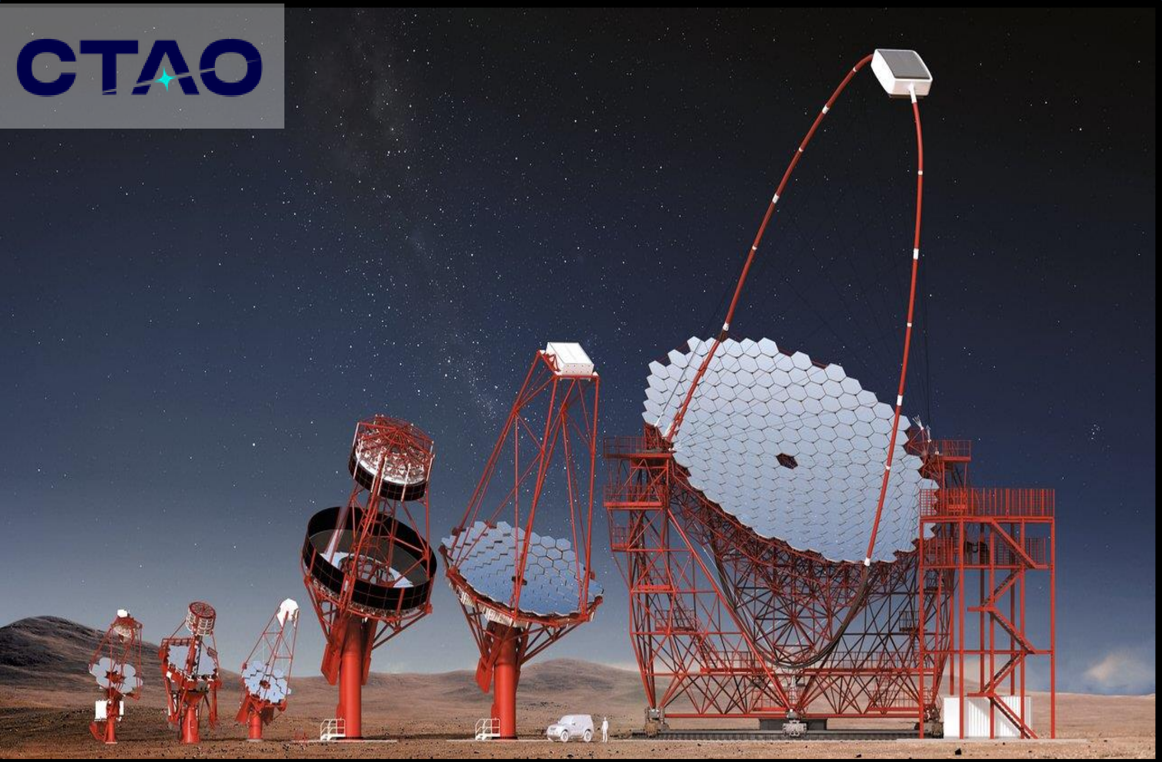
- Over 1000 targets
- Both NIRSpec and MIRI
- More statistics, better targets and broader mass coverage

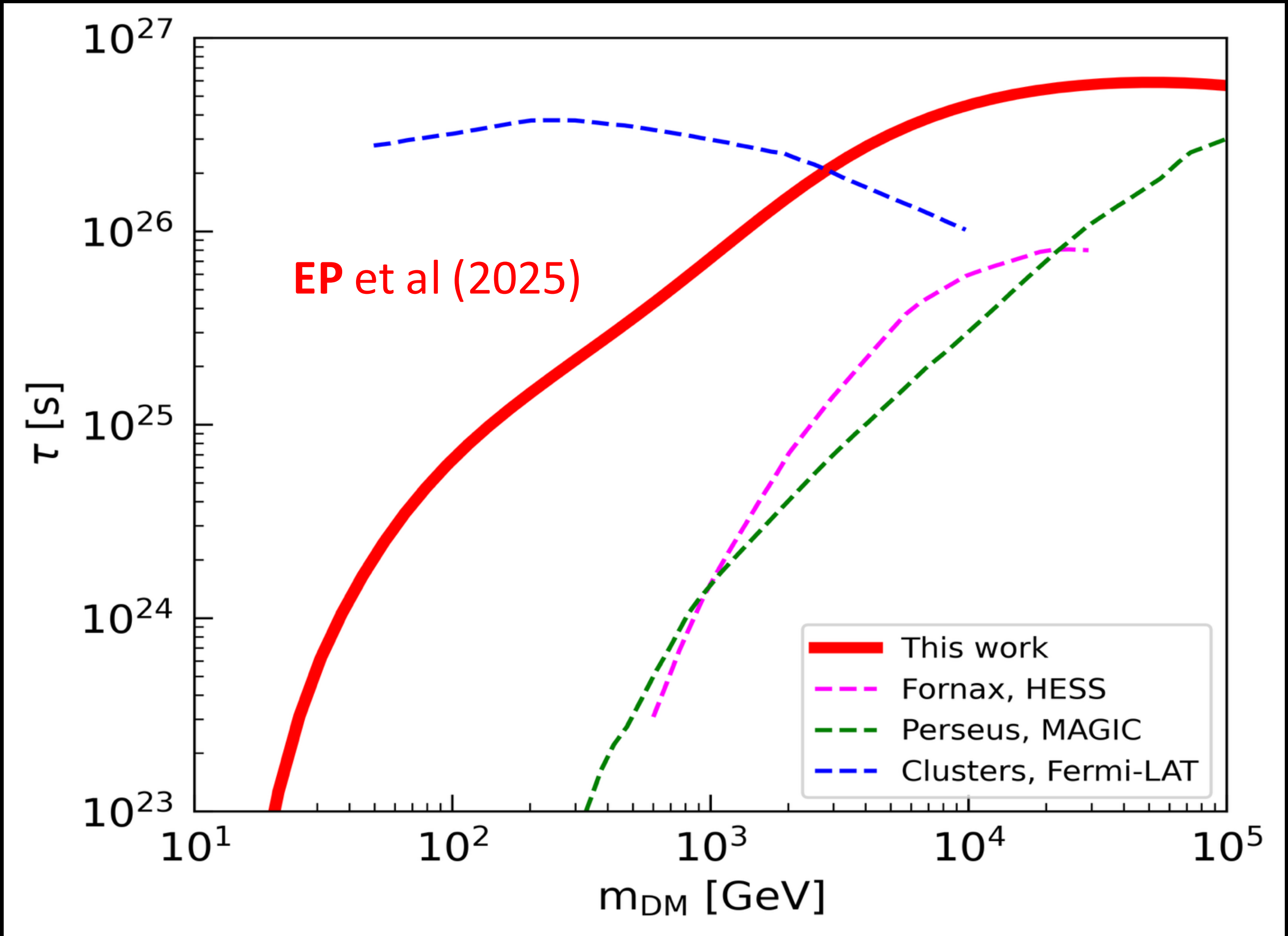
The Axion Landscape



Credit: C. OHare

Dark Matter Prospects with CTAO





Full-sky map (North & South arrays)

$E_{\gamma} \sim 20\ \mathrm{GeV} - 300\ \mathrm{TeV}$

First observations in 2026

Competitive for TeV dark matter searches